EPRA International Journal of Agriculture and Rural Economic Research (ARER)- Peer-Reviewed Journal
Volume: 13 | Issue: 12 | December 2025 | Journal DOI: 10.36713/epra0813| Impact Factor SJIF(2025): 8.733| ISSN: 2321 – 7847

# SUSTAINABLE CONTROL OF INVASIVE WEEDS IN INDIA: MYCOHERBICIDE PROGRESS AND MARKET PROSPECTS

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**Article DOI: https://doi.org/10.36713/epra25529**
**DOI No: 10.36713/epra25529**

**ABSTRACT**---------------------------------------------------------------------------------------------------------

*Invasive alien weeds pose severe ecological, agricultural, and socio-economic challenges across India, threatening biodiversity, ecosystem services, and crop productivity. Conventional management approaches, including mechanical removal and chemical herbicides, have demonstrated limited long-term effectiveness and are increasingly constrained by concerns related to environmental safety, herbicide resistance, and economic sustainability. In this context, mycoherbicides – bioherbicides derived from phytopathogenic fungi – represent promising alternatives for invasive weed management.*

*Recent advances have shifted emphasis from live fungal inocula toward cell-free broth formulations containing fungal metabolites, enzymes, and phytotoxins. These next-generation formulations offer improved biosafety, enhanced shelf-life, greater formulation stability, and more consistent field performance compared to conventional microbial products. This review synthesizes published scientific literature, policy documents, and market analyses to critically examine the current status of mycoherbicide research in India, with particular emphasis on major invasive weeds such as Lantana camara and Parthenium hysterophorus.*

*The paper evaluates technological progress, ecological relevance, regulatory frameworks, and market prospects, while identifying key constraints limiting large-scale adoption. Strategic pathways for commercialization are discussed in the context of forestry management, organic agriculture, plantation systems, and climate-smart land-use initiatives. By integrating biological, policy, and market perspectives, this review highlights opportunities for translating laboratory research into scalable weed management solutions and underscores the need for coordinated efforts among researchers, regulators, and industry stakeholders to mainstream mycoherbicides in sustainable weed management programs in India.*

**KEYWORDS:** *Biological Weed control. Mycoherbicides, Fungal metabolites, Cell-free broth formulations, Invasive alien weeds, Commercialization and regulatory pathways*----------------------------------------------------

## 1. INTRODUCTION

Biological invasions by alien plant species have emerged as a major ecological and agronomic challenge in India, with far-reaching consequences for biodiversity conservation, ecosystem functioning, and agricultural productivity (Sharma et al., 2005; Kumar & Babu, 2015). India's diverse agro-ecological landscapes—ranging from tropical forests and grasslands to intensively managed croplands—are particularly vulnerable to invasive weeds characterized by rapid growth, high reproductive capacity, phenotypic plasticity, and strong adaptive potential (Murthy et al., 2010). Species such as *Lantana camara*, *Parthenium hysterophorus*, *Chromolaena odorata*, and *Mikania micrantha* have expanded aggressively across forest ecosystems, plantations, rangelands, and agricultural fields, causing displacement of native flora, suppression of crop productivity, and degradation of ecosystem services (Sharma & Raghubanshi, 2009; Kaur et al., 2014; Bora et al., 2023). These invasions are further exacerbated by land-use change, climate variability, and anthropogenic disturbances, making long-term management increasingly complex.

Conventional weed management strategies in India have historically relied on mechanical removal and chemical herbicides. While mechanical methods are labor-intensive, costly, and often impractical at large spatial scales, chemical herbicides provide rapid suppression but suffer from several well-documented limitations. Repeated and indiscriminate use of synthetic herbicides has contributed to the evolution of herbicide-resistant weed populations, contamination of soil and water resources, and adverse effects on non-target organisms, including beneficial soil microbiota and native plant species (Heap, 2014; FAO, 2017). These limitations are particularly pronounced in forest ecosystems, protected areas, and plantation systems, where chemical interventions are ecologically undesirable or legally restricted (GIZ India, 2021). Against this background, the sustainability and long-term effectiveness of conventional weed control approaches are increasingly questioned, necessitating the exploration of environmentally benign alternatives.

Biological control of weeds has therefore gained renewed attention as a core component of sustainable weed management strategies. Among available biological approaches, mycoherbicides—bioherbicides derived from phytopathogenic fungi—represent a promising and ecologically sound option (Charudattan, 2001; Boyette et al., 2019). Mycoherbicides exploit natural antagonistic interactions between fungi and host plants and offer advantages such as host specificity, biodegradability, and compatibility with integrated pest management (IPM) frameworks (Pandey et al., 2018; Verma & Singh, 2020; Tiwari et al., 2024). Globally, several fungal pathogens have been evaluated as weed control agents, and limited commercial successes have demonstrated the technical feasibility of this approach under specific ecological and management conditions (Ray & Chakraborty, 2022; Hoagland et al., 2023).

In India, research on mycoherbicides has expanded steadily over the past two decades, with numerous studies reporting the isolation, characterization, and pathogenicity of indigenous fungal strains against major invasive weeds (Singh & Pandey, 2019; Chakraborty & Ray, 2021). Despite encouraging laboratory and greenhouse results, large-scale field adoption remains limited. A major constraint has been the inconsistent performance of live fungal inocula under variable field conditions, strongly influenced by temperature, humidity, ultraviolet radiation, and formulation stability (Singh & Pandey, 2020; Boyette et al., 2019). In addition, biosafety concerns related to the release of live pathogens, potential non-target effects, and complex regulatory requirements have further restricted commercialization efforts (CIBRC, 2023).

Recent advances in fungal biotechnology have shifted attention toward cell-free broth formulations, which utilize extracellular metabolites, enzymes, and phytotoxins produced during fungal fermentation rather than viable propagules (Pandey & Singh, 2020; Yadav & Joshi, 2021). These metabolite-based formulations represent a significant conceptual and technological advancement in bioherbicide development, offering improved biosafety, enhanced shelf-life, formulation consistency, and more predictable field performance (Ray & Chakraborty, 2022; Singh & Pandey, 2025). Importantly, by eliminating living fungal cells, such formulations reduce ecological risks associated with pathogen persistence and dispersal, while potentially simplifying regulatory evaluation.

India is uniquely positioned to benefit from metabolite-based mycoherbicides due to the convergence of three critical factors: exceptionally high fungal biodiversity, severe and widespread invasive weed pressure across forestry and agricultural systems, and increasing regulatory and societal constraints on chemical herbicide use. This convergence creates a favorable innovation landscape for developing non-living, biosafe bioherbicides tailored to local ecological and policy contexts.

Despite their promise, research on fungal metabolite-based mycoherbicides in India remains fragmented, with limited integration across biological efficacy, formulation science, regulatory assessment, and market readiness. A further limitation in the existing literature is the lack of comprehensive syntheses that connect laboratory-scale research with policy frameworks, commercialization pathways, and end-user adoption. While several reviews emphasize pathogenicity and bio-efficacy, fewer studies critically examine production scalability, regulatory approval processes, and alignment with national initiatives in forestry, organic agriculture, and climate-smart land management (FAO, 2017; GIZ India, 2021; Verma & Singh, 2020).

In view of these gaps, an integrated assessment that bridges scientific innovation with regulatory, economic, and policy dimensions is urgently needed. Such a synthesis is essential not only for advancing mycoherbicides as viable weed management tools but also for supporting India's broader objectives of sustainable agriculture, biodiversity conservation, and reduced dependence on chemical inputs (Kumar & Babu, 2015; Murthy et al., 2010).
Accordingly, the present review aims to:

- assess the current status of mycoherbicide research in India, with emphasis on fungal pathogens and priority invasive weed species;
- critically evaluate cell-free broth and fungal metabolite-based formulations as next-generation bioherbicides;
- analyze market potential, regulatory frameworks, and policy environments influencing commercialization; and
- identify strategic pathways for integrating mycoherbicides into sustainable weed management programs in agriculture and forestry.

## 2. INVASIVE WEEDS IN INDIA: DISTRIBUTION, IMPACTS AND MANAGEMENT CHALLENGES

India's vulnerability to invasive alien weeds is closely linked to its climatic heterogeneity, extensive forest cover, expanding plantation agriculture, and intensively managed cropping systems (Murthy et al., 2010; Kumar & Babu, 2015). Although more than 170 alien plant species have been reported as invasive in India, a relatively small subset accounts for a disproportionate share of ecological degradation and economic losses. These species are characterized by aggressive growth, high reproductive output, ecological plasticity, and the ability to dominate disturbed as well as semi-natural ecosystems (Sharma et al., 2005; Dogra et al., 2009) (Table 1).

**Table 1. Major invasive alien weeds in India, affected ecosystems, impacts, and management challenges**

| Weed Species | Primary Affected Ecosystems | Key Impacts | Major Management Challenges |
|---|---|---|---|
| *Lantana camara* | Forests, rangelands, protected areas | Suppresses native regeneration, alters fire regimes, reduces grazing capacity | Rapid regrowth after removal; unsuitability of chemical herbicides in forests |
| *Parthenium hysterophorus* | Croplands, pastures, roadsides, urban fringes | Crop yield loss, fodder contamination, human and livestock health hazards | Herbicide resistance risk; health risks during manual removal |
| *Chromolaena odorata* | Tea, coffee, rubber plantations | Competes with plantation crops; alters soil nutrient dynamics | Non-selective herbicides damage crops; high management costs |
| *Mikania micrantha* | Plantations, forest edges, wetlands | Smothers vegetation; reduces productivity and biodiversity | Regeneration from fragments; limited chemical control options |

Among the most problematic invasive weeds, *Lantana camara*, *Parthenium hysterophorus*, *Chromolaena odorata*, and *Mikania micrantha* have been widely recognized as national-level priorities due to their extensive distribution, resistance to conventional control measures, and long-term impacts on biodiversity, agricultural productivity, and ecosystem services (Sharma & Raghubanshi, 2009; Kaur et al., 2014; Bora et al., 2023). Rather than reiterating their well-documented ecological consequences, this section emphasizes ecosystem-specific dominance patterns and management constraints, thereby providing a clear rationale for mycoherbicide-based interventions.

### 2.1 Lantana Camara

*Lantana camara* is one of the most extensively distributed invasive shrubs in India, particularly dominating forest ecosystems in central, southern, and Himalayan foothill regions (Sharma & Raghubanshi, 2009; Murthy et al., 2010). Its invasive success is attributed to prolific seed production, vegetative regeneration, bird-mediated dispersal, and allelopathic suppression of native plant recruitment (Sharma et al., 2005; Singh et al., 2011). Dense lantana thickets severely restrict forest regeneration, alter fire regimes, reduce grazing capacity, and impede afforestation and biodiversity restoration programs.

Mechanical removal of *L. camara* is labor-intensive and often ineffective due to rapid resprouting, while chemical herbicides are largely unsuitable in forest ecosystems because of non-target risks, soil contamination, and regulatory restrictions (GIZ India, 2021). These limitations make *L. camara* a prime candidate for biological and bioherbicidal control approaches, particularly pathogen- and metabolite-based strategies that can operate under forest management constraints.

### 2.2 Parthenium Hysterophorus

*Parthenium hysterophorus* has emerged as one of the most problematic invasive weeds across agricultural landscapes, wastelands, and urban fringes in India (Kaur et al., 2014; Kumar & Babu, 2015). Its rapid life cycle, high seed output, and tolerance to a wide range of soil and climatic conditions enable aggressive colonization of croplands, grazing areas, and fallow lands. In agricultural systems, *Parthenium* causes significant yield losses, contaminates fodder, and reduces land value.

Chemical herbicides provide only short-term suppression, and repeated applications raise concerns regarding resistance development, environmental contamination, and rising production costs (Heap, 2014). Manual removal is associated with serious human and animal health risks, including dermatitis and respiratory disorders (Kaur et al., 2014). These factors highlight the urgent need for selective, environmentally safe control options, positioning *P. hysterophorus* as a key target for metabolite-based mycoherbicides in agricultural and peri-urban systems.

### 2.3 Chromolaena Odorata

*Chromolaena odorata* is a dominant invasive weed in plantation ecosystems, particularly tea, coffee, rubber, and coconut plantations in northeastern and southern India (Singh et al., 2012; Murthy et al., 2010). Its vigorous vegetative growth and dense canopy formation suppress understory vegetation, interfere with plantation management, and alter soil nutrient dynamics through allelopathic effects (Kumar & Tripathi, 2017).

Mechanical control is costly and requires frequent repetition, while non-selective chemical herbicides pose a high risk of phytotoxicity to perennial plantation crops. Consequently, biological control strategies, including fungal bioherbicides and metabolite-based formulations, are of particular interest in plantation systems where precision, selectivity, and environmental safety are critical (Verma & Singh, 2020).

### 2.4 Mikania Micrantha

*Mikania micrantha*, often described as one of the world's fastest-growing invasive vines, poses a serious threat to plantation crops, forest margins, wetlands, and riparian ecosystems, especially in northeastern India (Bora et al., 2023). Its climbing and smothering growth habit enables it to rapidly overgrow crops and native vegetation, leading to severe reductions in productivity and biodiversity.

Mechanical removal is largely ineffective due to regeneration from stem fragments, while chemical control is constrained by non-target effects in ecologically sensitive habitats (Dogra et al., 2009; GIZ India, 2021). These growth characteristics present unique management challenges that favor pathogen-based and metabolite-mediated suppression strategies capable of targeting vegetative tissues directly.

**Implications for Mycoherbicide Development**

The ecological dominance and management constraints associated with these invasive weeds underscore the limitations of conventional control strategies and justify the exploration of alternative approaches (Charudattan, 2001; Boyette et al., 2019). Importantly, these species dominate ecosystems where chemical herbicides are either ineffective, environmentally risky, or socially unacceptable, creating a clear niche for mycoherbicides and fungal metabolite–based bioherbicides (Verma & Singh, 2020; Ray & Chakraborty, 2022).

Their predictable dominance patterns, ecological specificity, and management sensitivity provide favorable conditions for the development of targeted, host-specific bioherbicidal solutions, particularly suited for forestry, plantation agriculture, organic farming, and low-input land-use systems in India.

## 3. MYCOHERBICIDES AND CELL FREE BROTH FORMULATIONS: CONCEPTS, MECHANISMS AND EMERGING ADVANTAGES

Mycoherbicides are biological weed control agents derived from phytopathogenic fungi that suppress or eliminate target weeds through infection processes or via the action of fungal secondary metabolites (Charudattan, 2001; Boyette et al., 2019). Unlike synthetic herbicides, which often exhibit broad-spectrum and non-selective toxicity, mycoherbicides typically display a high degree of host specificity, thereby minimizing adverse effects on non-target plant species and associated ecosystems (Pandey et al., 2018; Verma & Singh, 2020). This ecological selectivity makes mycoherbicides particularly attractive for weed management in forests, plantations, organic farming systems, and other environmentally sensitive landscapes.

Over the past several decades, two distinct technological approaches have evolved within mycoherbicide development: (i) formulations based on live fungal inocula and (ii) metabolite-based or cell-free broth formulations. Understanding the conceptual and functional differences between these approaches is essential for evaluating their ecological suitability, technological maturity, and commercial potential, particularly in the Indian context.

### 3.1 Live Fungal Inocula–Based Mycoherbicides

Conventional mycoherbicides rely on the application of viable fungal propagules, including spores, conidia, or mycelial fragments, which infect the target weed following application (Charudattan, 2001). Successful infection results in colonization of host tissues, disruption of physiological processes, and the development of disease symptoms such as chlorosis, necrosis, wilting, and eventual plant mortality. In India, fungal genera such as *Colletotrichum*, *Alternaria*, *Fusarium*, *Curvularia*, and *Phoma* have been extensively investigated for their pathogenicity against invasive weeds including *Lantana camara* and *Parthenium hysterophorus* (Singh & Pandey, 2019; Chakraborty & Ray, 2021).

Although live inocula-based mycoherbicides have demonstrated promising results under laboratory and greenhouse conditions, their performance under field conditions has frequently been inconsistent. Environmental factors such as temperature fluctuations, humidity levels, ultraviolet radiation, and rainfall significantly influence spore viability, germination, and infection efficiency (Boyette et al., 2019). In addition, maintaining the viability of live propagules during storage and transportation poses substantial formulation challenges, often resulting in limited shelf-life and variable efficacy (Singh & Pandey, 2020). These limitations have constrained large-scale adoption, particularly in tropical agro-ecosystems characterized by high environmental variability.

### 3.2 Metabolite-Based and Cell-Free Broth Formulations

In response to the limitations associated with live fungal inocula, research attention has shifted toward metabolite-based and cell-free broth formulations that utilize extracellular compounds produced during fungal fermentation (Pandey & Singh, 2020; Yadav & Joshi, 2021). These formulations exclude viable fungal cells and instead deliver biologically active metabolites, enzymes, and phytotoxins directly to the target weed. Weed suppression is mediated through multiple biochemical pathways, including membrane disruption, inhibition of photosynthetic processes, interference with plant hormonal balance, and induction of oxidative stress (Ray & Chakraborty, 2022). Studies demonstrate that fungal metabolites can reproduce—and in some cases exceed—the herbicidal effects observed with live pathogens, while avoiding many of the practical and ecological constraints associated with living organisms (Singh & Pandey, 2025). As a result, cell-free broth formulations are increasingly recognized as a next-generation platform for mycoherbicide development, particularly in regulatory environments where biosafety, formulation stability, and performance consistency are critical considerations (CIBRC, 2023).

### 3.3 Comparative Advantages of Cell-Free Broth Formulations

**Enhanced Biosafety**

One of the most significant advantages of cell-free broth formulations is improved biosafety. By eliminating viable fungal propagules, the risk of unintended spread, host switching, or long-term ecological persistence is substantially reduced (Charudattan, 2001; Verma & Singh, 2020). This attribute is particularly important in forest ecosystems, protected areas, and agroforestry systems, where the deliberate release of live pathogens may raise ecological and regulatory concerns. Empirical evidence demonstrates that metabolite-based formulations can achieve effective weed suppression without adversely affecting non-target plants, soil microbiota, or fauna (Ray & Chakraborty, 2022; Yadav & Joshi, 2021).

**Improved Shelf-Life and Formulation Stability**

Live fungal inocula are inherently sensitive to environmental conditions, resulting in limited shelf-life and logistical challenges during storage and transport. In contrast, cell-free broth formulations exhibit superior physicochemical stability, allowing for longer storage periods and improved batch-to-batch consistency (Pandey & Singh, 2020). Standardization of metabolite concentrations enhances predictability of field performance, which is essential for farmer acceptance and commercial scalability (Singh & Pandey, 2025).

**Regulatory Friendliness**

From a regulatory perspective, cell-free formulations may encounter fewer barriers than live microbial agents. Since these products do not contain living organisms, biosafety assessments related to pathogen survival, dispersal, and ecological establishment may be simplified (CIBRC, 2023). Evidence suggests that metabolite-based mycoherbicides can be evaluated under regulatory frameworks analogous to biochemical pesticides, potentially accelerating approval timelines and reducing compliance costs (Boyette et al., 2019; Ray & Chakraborty, 2022).

**Field Consistency and Performance Reliability**

Field-level inconsistency has been a major constraint of traditional mycoherbicides. Live inocula often require specific microclimatic conditions to establish infection, making efficacy unpredictable across locations and seasons (Boyette et al., 2019). In contrast, cell-free broth formulations act directly through phytotoxic compounds, reducing dependence on environmental conditions for pathogen establishment. Multiple studies demonstrate that metabolite-based formulations deliver more uniform weed suppression across diverse agro-climatic zones, thereby improving reliability under practical field conditions (Singh & Pandey, 2025; Yadav & Joshi, 2021).

### 3.4 Mechanistic Insights and Integration into Weed Management Systems

At the mechanistic level, fungal metabolites act through multiple biochemical targets, including degradation of cell walls, inhibition of photosynthetic electron transport, disruption of membrane integrity, and induction of oxidative stress pathways (Ray & Chakraborty, 2022). This multi-site mode of action reduces the likelihood of resistance development, a growing concern associated with repeated use of single-site chemical herbicides (Heap, 2014).

Moreover, metabolite-based mycoherbicides are highly compatible with integrated weed management and IPM frameworks. They can be combined with mechanical, cultural, or biological control practices to achieve synergistic and durable weed suppression (FAO, 2017; Verma & Singh, 2020). Their targeted action, environmental compatibility, and formulation stability position cell-free broth formulations as a strategic bridge between classical biological control and modern sustainable agriculture technologies.

## 4. RESEARCH STATUS OF MYCOHEBRICIDES IN INIDA: PROGRESS, GAPS AND TECHNOLOGY READINESS

India has made notable progress in the exploration of biological weed control, particularly through research on phytopathogenic fungi and their metabolites as environmentally compatible alternatives to chemical herbicides (Charudattan, 2001; Verma & Singh, 2020). Over the past two decades, a substantial body of experimental work has emerged from Indian research institutions, documenting fungal diversity, pathogenic interactions, and bioefficacy against major invasive weeds. However, despite this expanding knowledge base, the development of mycoherbicides in India remains uneven across different stages of innovation and commercialization (Singh & Pandey, 2019).

To critically assess the maturity of mycoherbicide research, existing studies are synthesized here under four interconnected domains—pathogen discovery, metabolite screening, formulation development, and field validation—and evaluated using a Technology Readiness Level (TRL) framework (Table 2). This approach enables systematic identification of strengths, bottlenecks, and priority areas for translational advancement.

**Table 2. Technology readiness status of mycoherbicide research in India**

| Research domain | Approximate TRL | Current status | Key limitations |
|---|---|---|---|
| Pathogen discovery | TRL 1–2 | Strong laboratory evidence | Limited host-range and non-target testing |
| Metabolite screening | TRL 2–3 | Proof-of-concept established | Poor metabolite characterization and standardization |
| Formulation research | TRL 3–4 | Early-stage development | Lack of scale-up and stability protocols |
| Field validation | TRL 4–5 | Limited pilot trials | Absence of multi-location, long-term studies |

### 4.1 Pathogen Discovery and Host Specificity Assessment (TRL 1–2)

Early-stage mycoherbicide research in India has focused predominantly on the isolation, identification, and pathogenicity evaluation of fungi associated with invasive weeds. Numerous studies have reported indigenous fungal taxa—particularly from the genera *Colletotrichum*, *Alternaria*, *Fusarium*, *Curvularia*, and *Phoma*—exhibiting disease-causing potential against priority weeds such as *Lantana camara*, *Parthenium hysterophorus*, and *Chromolaena odorata* (Singh & Pandey, 2019; Chakraborty & Ray, 2021).

At this TRL 1–2 stage, research has successfully established proof-of-concept for host–pathogen interactions and disease symptomatology under laboratory and greenhouse conditions. These studies form a strong biological foundation for mycoherbicide development and highlight India's rich reservoir of fungal biodiversity as a valuable resource. However, comprehensive host-range testing and non-target risk assessment remain limited. Most studies assess pathogenicity on target weeds alone, without systematic evaluation of effects on related crops, native plant species, or ecologically important non-target flora (Charudattan, 2001; Verma & Singh, 2020). This gap restricts progression toward regulatory approval and applied deployment.

### 4.2 Metabolite Screening and Phytotoxicity Evaluation (TRL 2–3)

Building upon pathogen discovery, research attention in India has increasingly shifted toward identifying fungal metabolites responsible for weed suppression. Several studies demonstrate that cell-free culture filtrates containing extracellular enzymes, organic acids, and secondary metabolites induce strong phytotoxic effects, often comparable to or exceeding those produced by live fungal inocula (Pandey & Singh, 2020; Yadav & Joshi, 2021). At the TRL 2–3 level, qualitative and semi-quantitative bioassays have consistently reported metabolite-mediated necrosis, chlorosis, and growth inhibition in weeds such as *Parthenium hysterophorus* and *Lantana camara* (Kaur et al., 2014; Singh & Pandey, 2025). These findings provide compelling evidence that fungal metabolites represent viable bioherbicidal agents. However, significant limitations persist. Most studies do not identify or chemically characterize the active compounds responsible for phytotoxicity, and standardized extraction, purification, and quantification protocols are largely absent (Ray & Chakraborty, 2022). Advanced analytical approaches, including LC–MS, GC–MS, and metabolomics, remain underutilized, limiting reproducibility and formulation standardization.

### 4.3 Formulation Development and Stability Optimization (TRL 3–4)

Formulation research represents a critical transition between experimental validation and product development. In India, limited but meaningful progress has been made in exploring formulation strategies that enhance the stability, shelf-life, and delivery efficiency of mycoherbicides (Boyette et al., 2019; Singh & Pandey, 2020).

Studies have examined fermentation optimization, use of adjuvants, and carrier materials to improve both live inocula and metabolite-based preparations.

Cell-free broth formulations have demonstrated particular promise at the TRL 3–4 stage due to their superior storage stability and reduced biosafety concerns (Pandey & Singh, 2020; Singh & Pandey, 2025). Nonetheless, formulation research remains fragmented and largely confined to laboratory-scale experiments. Challenges include maintaining consistent metabolite concentrations, ensuring compatibility with conventional spray equipment, optimizing dose–response relationships, and adapting formulations to diverse agro-climatic conditions (Ray & Chakraborty, 2022). The absence of standardized formulation protocols and pilot-scale production studies has limited cross-study comparability and delayed progression toward commercialization.

### 4.4 Field Validation and Pilot-Scale Trials (TRL 4–5)

Field validation represents the most underdeveloped component of mycoherbicide research in India. Only a limited number of pilot-scale field trials have been conducted, primarily in lantana-infested forest patches and parthenium-dominated agricultural landscapes (Singh & Pandey, 2019; Verma & Singh, 2020). These studies have reported variable but encouraging levels of weed suppression, confirming the potential applicability of fungal bioherbicides under real-world conditions.

At the TRL 4–5 stage, however, field trials remain geographically restricted, short-term, and insufficiently replicated. Multi-location and multi-season trials—essential for regulatory approval, farmer confidence, and economic evaluation—are largely absent (CIBRC, 2023). Furthermore, few studies incorporate comparative assessments against standard chemical herbicides or include cost–benefit analyses, limiting the ability to evaluate competitiveness and scalability (FAO, 2017). Addressing these gaps is critical for advancing mycoherbicides beyond experimental demonstrations.

### 4.5 Translational Challenges and Research Priorities

The TRL analysis reveals a pronounced imbalance in India's mycoherbicide research landscape, characterized by strong emphasis on early discovery stages and insufficient investment in translational research (Singh & Pandey, 2019; Boyette et al., 2019). Bridging this gap will require a strategic shift toward interdisciplinary collaboration integrating mycology, analytical chemistry, formulation science, agronomy, toxicology, and regulatory science (Ray & Chakraborty, 2022).

Priority research areas include systematic metabolite profiling, development of standardized fermentation and formulation protocols, and large-scale field validation across diverse agro-ecological zones (Pandey & Singh, 2020; FAO, 2017). Public–private partnerships, targeted funding mechanisms, and regulatory engagement at early development stages will be essential to advance promising candidates beyond the laboratory. Without such coordinated efforts, mycoherbicides in India are likely to remain confined to academic research rather than achieving tangible impact in invasive weed management.

## 5. PRODUCTION, SCALE UP AND FORMULATIONS ECONOMICS OF MYCOHERBICIDES

The transition of mycoherbicides from laboratory-scale innovation to commercially viable weed management products depend critically on production scalability, formulation robustness, and economic feasibility. While earlier sections highlight progress in pathogen discovery, metabolite screening, and formulation development at experimental scales, these advances must be supported by cost-effective production systems and scalable manufacturing pathways to enable widespread adoption. This section examines the key technical and economic considerations influencing large-scale production of mycoherbicides in India, with particular emphasis on cell-free broth and fungal metabolite–based formulations.

### 5.1 Fermentation and Upstream Production Considerations

At the core of mycoherbicide production lies fungal fermentation, which determines yield, consistency, and cost of bioactive metabolites. In India, most studies have relied on small-scale submerged fermentation using synthetic or semi-synthetic media optimized for laboratory experimentation (Pandey & Singh, 2020; Singh & Pandey, 2025). While such systems are suitable for proof-of-concept studies, they are not economically viable at commercial scale.

Scale-up requires optimization of upstream parameters, including nutrient composition, carbon and nitrogen sources, pH, aeration, agitation, and fermentation duration. The use of low-cost agro-industrial residues—such as molasses, rice bran, corn steep liquor, or oilseed cakes—as fermentation substrates represents a promising strategy for reducing production costs and improving economic viability (Boyette et al., 2019). India's abundant agricultural by-products provide a strategic advantage in developing cost-efficient fermentation systems for fungal metabolite production.

Cell-free broth formulations offer an additional advantage at the upstream level, as they eliminate the need to maintain propagule viability, allowing greater flexibility in fermentation conditions and harvesting schedules. This flexibility can significantly simplify scale-up and reduce batch failure risks compared to live inocula–based systems.

**5.2 Downstream Processing and Formulation Scale-Up**

Downstream processing—including filtration, clarification, concentration, and stabilization of metabolites—represents a major cost component in mycoherbicide production. For live fungal products, downstream processing must preserve spore or mycelial viability, which imposes strict constraints on temperature, moisture, and handling. In contrast, metabolite-based formulations allow more robust processing options, including heat treatment, pH adjustment, and chemical stabilization, without compromising bioefficacy (Ray & Chakraborty, 2022).

Formulation scale-up requires balancing biological efficacy with storage stability, ease of application, and compatibility with conventional spray equipment. Liquid formulations, wettable concentrates, and emulsifiable preparations have shown promise for cell-free broths, particularly in forestry and plantation contexts where precision application is required (Pandey & Singh, 2020). However, maintaining consistent metabolite concentrations across batches remains a challenge, underscoring the need for standardized quality control protocols and metabolite quantification benchmarks.

**5.3 Cost Structure and Economic Feasibility**

The economic feasibility of mycoherbicides is influenced by multiple cost components, including fermentation inputs, downstream processing, formulation additives, packaging, regulatory compliance, and distribution. Compared to chemical herbicides, mycoherbicides may initially appear costlier on a per-unit basis. However, this comparison often overlooks indirect benefits such as reduced environmental remediation costs, improved ecosystem services, and compatibility with organic and low-input farming systems (FAO, 2017).

Cell-free broth formulations offer distinct economic advantages by reducing losses associated with viability decline, cold-chain storage, and short shelf-life. Moreover, simplified regulatory pathways for non-living bioherbicides could substantially reduce data generation costs and approval timelines, improving return on investment (CIBRC, 2023). For institutional buyers—such as forestry departments and plantation estates—cost-effectiveness is often evaluated at the system level rather than per-application cost, further favoring metabolite-based solutions.

**5.4 Production Models and Institutional Pathways**

Multiple production and deployment models are relevant for mycoherbicides in India. Public-sector research institutions and universities have traditionally driven early-stage development but lack infrastructure for large-scale manufacturing.

Public–private partnerships (PPPs) provide a viable pathway for bridging this gap. Under such models, public institutions can focus on strain development, metabolite optimization, and efficacy validation, while private partners manage scale-up, formulation refinement, regulatory registration, and market distribution (Singh & Pandey, 2019). Decentralized production models, particularly for forestry and regional invasive weed management programs, may also be feasible for cell-free formulations due to their relative production simplicity and storage stability.

**5.5 Linking Production Economics to Market Adoption**

Production scalability and formulation economics directly influence market adoption, particularly in cost-sensitive agricultural systems. Products targeting niche markets—such as forestry, organic farming, and plantation agriculture—can tolerate higher initial costs due to limited alternatives and regulatory constraints on chemical herbicides. Success in these segments can generate confidence, operational experience, and revenue streams necessary for gradual market expansion.

Importantly, the economic viability of mycoherbicides should be evaluated within a phased commercialization framework, aligning production scale with TRL progression and market readiness. Premature large-scale manufacturing without validated field performance and regulatory clarity risks undermining commercial credibility. Conversely, strategically aligned scale-up efforts can accelerate the transition from experimental formulations to reliable, field-ready products.

## 6. MARKET POTENTIAL AND FINANCIAL OUTLOOK FOR MYCOHERBICIDES IN INDIA

The market potential for mycoherbicides in India must be evaluated within the broader transformation of the country's crop protection and land management sectors toward sustainability, reduced chemical dependence, and regulatory compliance. While chemical herbicides currently dominate due to rapid efficacy and established supply chains, growing challenges—including herbicide resistance, labor shortages, stricter environmental regulations, and demand for residue-free produce—are creating strategic entry points for biological alternatives such as mycoherbicides (FAO, 2017; Singh & Pandey, 2019).

Insights from production and scale-up economics (Section 5) indicate that mycoherbicides, particularly cell-free fungal metabolite–based formulations, are best positioned as phased, niche-market solutions rather than immediate mass-market replacements for synthetic herbicides. Their commercial viability depends on aligning production scale, formulation stability, and regulatory readiness with clearly defined use environments where chemical options are constrained or undesirable.

### 6.1 Overview of the Indian Herbicide and Bioherbicide Market

The Indian herbicide market continues to expand, driven by rising weed pressure, mechanization, and labor scarcity. However, the bioherbicide segment remains relatively small, reflecting limited product availability and lower awareness among end users (Verma & Singh, 2020). Within this segment, mycoherbicides represent a high-potential but underdeveloped category, constrained more by production and regulatory bottlenecks than by biological efficacy.

Market analyses suggest that biological weed control products are unlikely to compete with chemical herbicides on price alone in the short term. Instead, their value proposition lies in system-level benefits, including environmental compliance, ecosystem protection, and suitability for organic and low-input farming systems. Cell-free broth formulations improve market readiness by offering better shelf-life, batch consistency, and simplified logistics compared to live inocula–based products, thereby reducing commercialization risk (Singh & Pandey, 2025).

### 6.2 Priority Market Segments Linked to Production Feasibility

**Forestry and Afforestation Programs**

Forestry represents the most immediate and strategically important market segment for mycoherbicides in India. Large-scale invasive weed management initiatives targeting *Lantana camara* and *Chromolaena odorata* operate under strict environmental and regulatory constraints that limit chemical herbicide use (GIZ India, 2021). As discussed in Section 5, institutional buyers in forestry evaluate cost-effectiveness at the program level rather than per-application cost, favoring metabolite-based formulations with high biosafety and operational reliability.
Government-supported initiatives, including CAMPA-funded programs, offer opportunities for bulk procurement and demonstration-driven adoption, making forestry an ideal entry point for early commercialization.

**Organic and Low-Input Farming Systems**

Organic agriculture prohibits synthetic herbicides, leaving farmers with limited weed management options. Although production costs for mycoherbicides may be higher than conventional herbicides, cell-free formulations offer economic feasibility in organic systems by reducing labor dependence and enabling selective weed suppression (FAO, 2017; Yadav & Joshi, 2021). Smaller production batches aligned with regional demand can further improve cost efficiency, as highlighted in decentralized production models discussed in Section 5.

**Plantation Agriculture (Tea, Coffee, Rubber)**

Plantation systems are particularly sensitive to non-selective herbicides due to crop phytotoxicity risks and long crop life cycles. Invasive weeds such as *Chromolaena odorata* and *Mikania micrantha* impose high recurring management costs in these systems (Singh et al., 2012; Bora et al., 2023). Targeted mycoherbicides, though potentially higher in unit cost, can reduce repeated manual weeding and long-term ecological degradation, offering favorable cost–benefit dynamics for plantation operators.

### 6.3 Financial Outlook and Phased Commercialization Strategy

The financial outlook for mycoherbicides in India is best understood through a phased commercialization framework, closely aligned with TRL progression and production scalability (Singh & Pandey, 2020).

- Short term (1–3 years): Limited commercialization through institutional buyers, pilot programs, and government-supported demonstrations. Production volumes remain modest, focusing on cell-free formulations to minimize economic risk.

- Medium term (3–6 years): Expansion into niche commercial markets, including organic farming cooperatives and plantation sectors. Public–private partnerships play a critical role in scaling fermentation, formulation, and distribution capacity.
- Long term (6–10 years): Broader market penetration supported by standardized production protocols, regulatory clarity for non-living bioherbicides, and improved farmer awareness. At this stage, economies of scale and optimized fermentation inputs can significantly reduce unit costs (Section 5).

Importantly, premature large-scale manufacturing without validated field performance and regulatory alignment could undermine market confidence. A measured scale-up approach, integrating technical readiness with demand forecasting, is therefore essential.

### 6.4 Investment Climate and Commercial Risk Considerations

Despite strong scientific foundations, private investment in mycoherbicides remains cautious due to long development timelines. However, cell-free broth formulations reduce several commercial risks by improving shelf-life, simplifying logistics, and potentially shortening regulatory approval processes (CIBRC, 2023). From an economic perspective, mycoherbicides should be positioned not as low-cost substitutes but as value-added inputs delivering environmental compliance, resistance management, and long-term sustainability benefits. Aligning pricing strategies with these value propositions is critical for market acceptance.

## 7. POLICY AND REGULATORY FRAMEWORK FOR MYCOHERBICIDES IN INDIA: CHALLENGES, GAPS AND REFORM PATHWAYS

The successful transition of mycoherbicides from experimental research to field-ready and commercially viable weed management tools in India is critically dependent on an enabling regulatory and policy environment. While India has established a comprehensive pesticide regulatory framework, the system was primarily designed for synthetic chemical pesticides and, to a lesser extent, for living microbial agents. Consequently, emerging bioherbicide technologies—particularly cell-free fungal metabolite–based formulations—do not align neatly with existing regulatory categories, creating ambiguity, delays, and uncertainty for developers and investors.

### 7.1 Existing Regulatory Oversight under the Insecticides Act

In India, the Central Insecticides Board and Registration Committee (CIBRC), operating under the Insecticides Act, 1968, is the statutory authority responsible for the registration of herbicides, bioherbicides, and other crop protection products. All products intended for commercial use must undergo evaluation for efficacy, toxicology, environmental safety, and non-target effects prior to approval.

For microbial biopesticides, including live fungal mycoherbicides, the CIBRC has issued specific guidelines addressing strain identity, pathogenicity, host specificity, and biosafety. These guidelines are scientifically rigorous and appropriate for living organisms capable of replication and environmental persistence. However, when applied to non-living, metabolite-based formulations, these same requirements often result in disproportionate data demands that do not accurately reflect actual risk profiles (CIBRC, 2023).

### 7.2 Regulatory Challenges Specific to Metabolite-Based Mycoherbicides

The primary regulatory challenge for metabolite-based mycoherbicides is the absence of a distinct regulatory category recognizing their non-living nature. Although these products do not contain viable organisms, they are frequently evaluated under microbial pesticide frameworks, requiring data related to pathogen survival, dispersal, and host range that are not scientifically relevant.

### 7.3 International Regulatory Context and Lessons for India

Globally, regulatory systems are increasingly differentiating between living microbial agents and non-living biochemical or metabolite-based pesticides. In several jurisdictions, fungal metabolites are assessed under biochemical pesticide frameworks that emphasize:

- Toxicological safety to humans and non-target organisms
- Environmental fate and degradation pathways
- Consistency and standardization of active compounds

These frameworks exclude requirements related to organism survival or ecological establishment, thereby aligning regulatory scrutiny with actual risk. Such models demonstrate that regulatory flexibility can coexist with robust safety standards, providing valuable reference points for reform in India.

### 7.4 Need for a Dedicated Regulatory Category for Non-Living Bioherbicides

A key policy priority emerging from recent research is the establishment of a separate regulatory category for non-living bioherbicides, including cell-free fungal broth formulations and purified fungal metabolites. Under such a framework, regulatory evaluation would be risk-based and mode-of-action–specific, rather than organism-based.

Proposed assessment criteria could include:

- Acute and chronic toxicity to humans and livestock
- Effects on non-target plants and beneficial organisms
- Environmental persistence, mobility, and degradation
- Batch consistency and quality control standards

By contrast, requirements related to pathogen viability, reproduction, and ecological persistence—critical for live microbial agents—would not apply. This differentiation could substantially reduce regulatory burden while maintaining environmental and human safety.

### 7.5 Policy Integration with National Sustainability Programs

Beyond regulatory reform, policy integration across national programs is essential for mainstreaming mycoherbicides. Initiatives such as the National Mission on Sustainable Agriculture (NMSA), Integrated Pest Management (IPM) programs, CAMPA-funded forestry interventions, and organic farming missions provide institutional platforms for adoption.
Explicit recognition of mycoherbicides and metabolite-based bioherbicides within these programs would:

- Enhance product legitimacy
- Support government-backed demonstration trials
- Enable public procurement during early commercialization phases

Such integration is particularly important for forestry and plantation systems, where institutional adoption can drive scale and visibility before broader market penetration.

### 7.6 Institutional Support, Incentives, and Capacity Building

To accelerate adoption, regulatory reform must be complemented by institutional support mechanisms. These include targeted funding for translational research, incentives for public–private partnerships, and capacity building within regulatory agencies to evaluate novel bioherbicide technologies.
Government-supported pilot programs, risk-sharing procurement models, and innovation grants can significantly reduce early-stage commercial risk. At the same time, training programs for extension agencies and forest managers are needed to improve awareness and correct application practices, ensuring that policy intent translates into field-level impact.

### 7.7 Future Policy Directions

To unlock the full potential of mycoherbicides in India, regulatory and policy frameworks must evolve in parallel with scientific and technological innovation. Priority actions include:

- Establishing clear, science-based guidelines for metabolite-based bioherbicides
- Streamlining approval pathways for non-living biological products
- Encouraging early dialogue between regulators, researchers, and industry
- Aligning bioherbicide development with national sustainability and climate goals

By modernizing regulatory pathways and integrating mycoherbicides into broader agricultural and forestry policies, India can not only address its domestic invasive weed challenges but also position itself as a global leader in sustainable weed management technologies.

## 8. SWOT ANALYSIS AND STRATEGIC ROADMAP FOR MYCOHERBICIDE DEVELOPMENT IN INDIA

Despite strong scientific foundations and growing policy interest, the large-scale deployment of mycoherbicides in India remains constrained by translational, regulatory, and market-related challenges. A structured SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis provides a holistic assessment of the current landscape and serves as a basis for developing a realistic strategic roadmap. This approach enables alignment of technological readiness, production feasibility, regulatory reform, and market adoption into a coherent development pathway.

### 8.1 Strengths

India possesses several intrinsic strengths that favor the development and deployment of mycoherbicides, particularly metabolite-based formulations.

First, the country's exceptional fungal biodiversity offers a rich reservoir of phytopathogenic species and bioactive metabolites with weed-specific activity. Indigenous strains adapted to local agro-climatic conditions increase the likelihood of efficacy and ecological compatibility. Second, a strong public-sector research ecosystem—including agricultural universities, ICAR institutes, and forestry research centers—has generated substantial baseline knowledge on invasive weeds, host–pathogen interactions, and fungal metabolites.

Third, the emergence of cell-free broth and metabolite-based technologies represents a major technical advantage. As highlighted in Sections 4 and 5, these formulations overcome many limitations associated with live microbial inocula, including short shelf-life, biosafety concerns, and inconsistent field performance. Finally, increasing policy emphasis on sustainable agriculture, residue-free food production, and ecosystem restoration strengthens institutional receptivity to bioherbicides.

**8.2 Weaknesses**

Notwithstanding these strengths, several internal weaknesses limit progress toward commercialization. A key constraint is the fragmentation of research efforts, with most studies concentrated at early TRL stages and limited continuity from discovery to field validation. Advanced metabolite characterization, formulation standardization, and multi-location field trials remain underdeveloped.

From an economic perspective, scale-up and cost optimization studies are scarce, leading to uncertainty regarding production economics and pricing strategies. Additionally, limited engagement between academic researchers and industry partners has slowed translation of promising candidates into market-ready products.

Regulatory ambiguity—particularly for non-living metabolite-based bioherbicides—further exacerbates these weaknesses by increasing development costs and discouraging private investment (Section 7).

**8.3 Opportunities**

External opportunities for mycoherbicides in India are substantial and expanding. Growing resistance to chemical herbicides, labor shortages, and environmental restrictions are driving demand for alternative weed management strategies. Forestry, plantation agriculture, organic farming, and ecologically sensitive landscapes represent high-opportunity niche markets where mycoherbicides can deliver clear comparative advantages (Section 6).

India's access to low-cost agro-industrial residues provides an opportunity to develop economically competitive fermentation systems, particularly for metabolite-based formulations. Moreover, international interest in sustainable crop protection creates potential for export-oriented development, positioning India as a regional hub for bioherbicide innovation.

Policy reforms recognizing non-living bioherbicides as a distinct category could further unlock opportunities by reducing regulatory friction and accelerating market entry.

**8.4 Threats**

Key external threats include competition from rapidly evolving chemical herbicides and integrated weed management technologies that offer immediate, broad-spectrum control. Inconsistent field performance of early bioherbicide products could undermine stakeholder confidence if not supported by robust validation.

Regulatory delays and lack of harmonization with international frameworks pose additional risks, particularly for small enterprises. Finally, inadequate farmer awareness and extension support could limit adoption, even where products demonstrate technical and environmental advantages.

**8.5 Strategic Roadmap for Advancement**

To convert scientific potential into practical impact, a phased strategic roadmap is essential:

Phase I: Consolidation and Validation (Short term, 1–3 years)

- Prioritize metabolite-based candidates with strong laboratory and greenhouse efficacy
- Invest in metabolite profiling, formulation stability, and pilot-scale fermentation
- Conduct targeted field trials in forestry and plantation systems
- Initiate early regulatory dialogue for non-living bioherbicides

Phase II: Translation and Market Entry (Medium term, 3–6 years)

- Establish public–private partnerships for scale-up and registration
- Develop standardized quality control and cost benchmarks
- Integrate mycoherbicides into government-supported invasive weed programs
- Strengthen extension and demonstration activities

Phase III: Expansion and Integration (Long term, 6–10 years)

- Expand into broader agricultural markets through integrated weed management
- Achieve cost reductions via optimized substrates and economies of scale
- Align products with climate-smart agriculture and restoration initiatives
- Explore export opportunities and international regulatory alignment

### 8.6 Synthesis and Forward Outlook

The SWOT analysis underscores that the primary barriers to mycoherbicide deployment in India are not biological feasibility but systemic and institutional limitations. By strategically aligning research priorities, production economics, regulatory reform, and market segmentation, mycoherbicides—particularly cell-free broth formulations—can transition from niche innovations to mainstream tools for invasive weed management.

This roadmap provides a practical framework for researchers, policymakers, and industry stakeholders to collaboratively advance sustainable weed management solutions tailored to India's ecological and socio-economic realities.

## 9. CONCLUSIONS AND FUTURE PERSPECTIVES

Invasive alien weeds continue to pose a persistent and escalating threat to India's agricultural productivity, forest ecosystems, and biodiversity. Conventional weed management strategies—dominated by mechanical interventions and synthetic herbicides—have demonstrated limited long-term effectiveness and are increasingly constrained by herbicide resistance, environmental degradation, regulatory restrictions, and socio-economic challenges (FAO, 2017; Verma & Singh, 2020). Against this background, mycoherbicides have emerged as scientifically credible and ecologically compatible alternatives for sustainable weed management.

This review critically synthesizes the current status of mycoherbicide research in India, highlighting substantial progress in fungal pathogen discovery, metabolite screening, and proof-of-concept efficacy studies against priority invasive weeds such as *Lantana camara*, *Parthenium hysterophorus*, and *Chromolaena odorata* (Charudattan, 2001; Singh & Pandey, 2019). The analysis clearly demonstrates that India possesses a strong biological and research foundation, supported by rich fungal biodiversity and an active public-sector research ecosystem.

A key conceptual advancement emphasized in this review is the transition from live fungal inocula toward cell-free broth and metabolite-based bioherbicides. These next-generation formulations address many of the limitations associated with traditional microbial products, including short shelf-life, biosafety concerns, batch inconsistency, and logistical constraints (Pandey & Singh, 2020; Ray & Chakraborty, 2022). From both a technological and regulatory perspective, metabolite-based approaches are better aligned with India's current policy environment and commercialization realities.

The Technology Readiness Level (TRL) assessment reveals a pronounced imbalance in the development pipeline. While early-stage research (TRL 1–3) is well developed, critical gaps persist at the formulation optimization, field validation, and scale-up stages (TRL 4–6). As demonstrated in Sections 4 and 5, the principal bottlenecks are not biological efficacy but rather deficiencies in translational research, standardized production protocols, and economic feasibility analyses (Boyette et al., 2019; Singh & Pandey, 2025).

Market analysis further indicates that mycoherbicides are unlikely to succeed as immediate, broad-spectrum replacements for chemical herbicides. Instead, their greatest potential lies in phased, niche-market deployment, particularly in forestry, plantation agriculture, organic farming systems, and ecologically sensitive landscapes where chemical options are restricted or undesirable (FAO, 2017; Bora et al., 2023). Institutional procurement and government-supported invasive weed management programs offer critical entry points for early commercialization.

Regulatory assessment underscores the urgent need for reform. The absence of a distinct regulatory category for non-living bioherbicides under the existing Insecticides Act framework creates unnecessary barriers for metabolite-based products (CIBRC, 2023). Establishing science-based, risk-proportionate guidelines that differentiate between living microbial agents and non-living fungal metabolites would significantly reduce development timelines and improve investor confidence, without compromising environmental or human safety.

From a strategic standpoint, the SWOT analysis and roadmap presented in this review highlight that the successful deployment of mycoherbicides in India will require coordinated, multi-stakeholder action. Priority future directions include:

(i) Advanced metabolite characterization using modern analytical tools;
(ii) Development of standardized, low-cost fermentation and formulation protocols utilizing agro-industrial residues;
(iii) Multi-location, multi-season field trials linked to regulatory requirements;
(iv) Early and continuous engagement with regulatory authorities; and
(v) Integration of mycoherbicides into national sustainability, forestry, and climate-resilience programs.

In conclusion, mycoherbicides—particularly cell-free fungal metabolite–based formulations—represent a scientifically sound and strategically viable component of India's sustainable weed management portfolio. Their successful translation from laboratory innovation to field application will depend not only on continued biological research but also on regulatory modernization, economic realism, and policy integration. With targeted investment and institutional support, India is well positioned to emerge as a global leader in bioherbicide innovation, contributing meaningfully to invasive weed management, ecosystem restoration, and climate-smart agriculture.

## ACKNOWLEDGEMENT

The authors express their sincere gratitude to the Head, Department of Biological Sciences, Rani Durgawati University, Jabalpur, Madhya Pradesh, for providing the necessary facilities and support to carry out this work. Financial assistance received from the Council of Scientific and Industrial Research (CSIR), Government of India, is gratefully acknowledged.

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