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Weed management scenario and prospects of herbicide tolerant crop technology in India

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Indian agriculture is the second largest contributor to the Indian economy. Globally, India ranks as the largest producer of pulses, cotton, cattle, milk, and jute and holds the second position in the production of rice, wheat, sugarcane, cotton, groundnuts, fruits, and vegetables. It is estimated that India, a country with one-fifth of the world population, needs a net quantity of 529 MT of food grains by 2050 for its food security. Although India's 2022 foodgrain production is estimated at record 316 MT, with limited or no scope of horizontal expansion in crop area and rapid urbanization in existing crop lands, producing more food per unit area is becoming a challenge. One of the consistent and major obstacles in improving production efficiency is weed infestation in crop fields. Weeds exhibit rapid growth and extensive foliage development to suppress crop growth, and this intensive competition often deprives the main crop of the inputs required for optimal development, ultimately leading to significant yield losses or even crop failure. Although, the western countries, especially North and South American and Australia, have adopted herbicide tolerant (HT) crops, which ensures minimum or no damage to the main crops while killing the weeds by selective herbicide application, India is yet to embrace this technology. Regardless, Indian agriculture consumes a significant volume of herbicide across the crops even in the absence of HT crops. The distinctive socio-political context in India, combined with resistance from certain sections of society toward genetic engineering, has been a major factor underlying the rejection of genetically modified HT cultivars. However, with rapid transition of labor force to non-agricultural professions leading to increasing cost of manual weed control and the lack of adequate advancement in cultural and mechanical weed control tools, the pressing demand of producing significantly more food is currently a challenge for Indian agriculture. We summarize in this article the situation that indicates whether Indian agriculture, given the greater responsibility of safeguarding its demanding food requirement while maintaining the export volume, should welcome HT crop cultivars, especially in the situation of rapidly increasing labor cost.

KEYWORDS

herbicide resistance, herbicide tolerance, mulching, transgenic development, weed management

1 Introduction

It is estimated that India, home to nearly one-fifth of the world's population, will require approximately 529 million tonnes of food grains by 2050 (Jain, 2011). To combat the situation, Indian agriculture has witnessed a tremendous growth in food grain production in last few decades. Having a net cropped area of 180.11 million ha (Mha), India ranks in first four countries in terms of agricultural production and first or second rank in total production of several important crops (Table 1). Recently India claimed to become self-sufficient in food production, however, high export rate of agricultural produces and large population pressure bring down the net food grain availability in the country to significantly below the potential national requirement. Ensuring food security by increased agricultural productivity is constantly challenged by various biotic and abiotic stresses (Ali et al., 2025a, Ali et al., 2025b). Among these, weed infestation poses as a formidable threat, capable of causing substantial yield losses in Indian agriculture, sometimes ranging from 20% to over 80% depending on the crop, weed species, and environmental conditions (Ramesh, 2015; Kaur et al., 2024). Traditional weed management practices in India, primarily manual weeding and backpack spraying, are labor-intensive, time-consuming, and increasingly uneconomical due to rising labor costs and scarcity, particularly during peak seasons (Table 2) (Chaudhary et al., 2023; Kumar et al., 2025). While chemical herbicides offer an efficient alternative, India is yet to embrace the herbicide-tolerant (HT) crop technology that allows non-selective application broad-spectrum herbicides enabling largescale mechanized farming. Moreover, Indian policymakers and stakeholders are still critically concerned about the indiscriminate use of herbicides that can lead to environmental concerns, herbicide resistance evolution in weeds, and potential health hazards in India if HT cultivars are intensively introduced (Parven et al., 2025).

HT crop cultivars have emerged as an important technological innovation worldwide, offering a potential solution to the increasing challenges of weed management (Nath et al., 2024). These cultivars are genetically engineered or developed through conventional

breeding methods to survive the application of specific broad-spectrum herbicides, allowing farmers to effectively control a wide range of weeds without harming the crop itself. The primary advantages of HT crops include simplified weed management, reduced labor requirements, improved weed control efficacy, enhanced crop yield stability, and the potential for reduced tillage practices, which can contribute to soil health and carbon sequestration (Green, 2012). Globally, HT crops, particularly those tolerant to glyphosate and glufosinate-AM, have seen widespread adoption, transforming agricultural practices in many major food-producing nations (Ofosu et al., 2023).

The adoption and integration of HT crop technology into Indian agriculture presents a unique set of complexities (Sekhar et al., 2024). India's agricultural landscape is characterized by diverse agro-climatic zones, predominantly small and marginal farmers, complex socio-economic structures, and a stringent regulatory framework for genetically modified organisms (GMOs). While the potential of HT crops in addressing issues of arable weed pressure, farmer profitability, and resource utilization in India are substantial, their widespread acceptance is contingent upon careful consideration of various factors. These include ensuring environmental safety, preventing the evolution and spread of herbicide-resistant weeds, managing potential socio-economic impacts on rural labor, and establishing robust regulatory and stewardship mechanisms. Moreover, it needs a careful approach to win over resistance from several environmental and social activists.

This paper aims to provide a meaningful overview of the current weed control measures, economic implications of the lack of HT Crops, impact of suspected spurious HT seed available in the market, and current scenario of HT research in Indian agriculture. The present review also highlights the multifaceted challenges associated with sub-optimal use of herbicide doses and associated resistance development. Through synthesizing existing knowledge and highlighting key issues, this analysis seeks to contribute to informed decision-making regarding the future trajectory of HT crop technology in India, ensuring that agricultural advancements serve both productivity goals and long-term ecological and societal well-being.

TABLE 1 Final estimate of production of major crops for the 2024-25.

| Crop | Production (million tonnes) | World rank | Crop | Production (million tonnes) | World rank |
|---|-----------------------------|-----------------|---|-----------------------------|-----------------|
| Rice | 150.18 | 2 nd | *Jute and Mesta (in Lakh Bales, 1 Bale =180 kg) | 84.88 and 3.13 | 1 st |
| Wheat | 117.94 | 2 nd | Nutri/Coarse Cereals (Maize + Barley + Total Millets) | 63.92 | - |
| Maize | 43.40 | 7 th | Groundnut | 11.94 | 2 nd |
| Total Millets | 18.59 | 1 st | Soybean | 15.26 | 5 th |
| Total Pulses | 25.68 | 1 st | Rapeseed & Mustard | 12.66 | 3 rd |
| Sugarcane | 454.61 | 2 nd | Gram | 11.11 | 1 st |
| *Cotton (in Lakh Bales, 1 Bale =170 kg) | 297.24 | 2 nd | Tur | 3.62 | 1 st |

Directorate of Economics and Statistics, Ministry of Agriculture & Farmers Welfare, Government of India (<https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/nov/doc20251120700901.pdf>).

TABLE 2 Cost of weed management in major crops in India (based on authors' experiences).

| Crop* | Av. labor cost (A ⁻¹)** (₹) | Cal. herbicide cost (A ⁻¹)*** (₹) |
|-----------|---|---|
| Rice | 16,200 | 1,780 |
| Wheat | 13,500 | 2,140 |
| Maize | 13,500 | 2,920 |
| Cotton | 24,300 | 1,910 |
| Soybean | 8,100 | 4,640 |
| Sugarcane | 24,300 | 1,920 |

*Rice: 2 weeding × 18 labors, wheat and maize: 2 weeding × 15 labors, cotton and sugarcane: 3 weeding × 18 labors.

**Labor cost per day is Rs. 450 [~\$5.12].

***PRE and POST herbicides + labor charges.

2 Current weed management practices in India

Traditionally, Indian farmers have managed weeds through cultural practices such as intensive tillage, crop rotation, manual and mechanical weeding, cover cropping, burning, puddling, and waterlogging in rice fields (Rao and Chauhan, 2015; Ghosh et al., 2021; Meena et al., 2025) (Table 3). Use of chemical herbicides in India began in 1937 with sodium arsenite to control wild

safflower (*Carthamus oxycantha*) in Punjab (Mishra et al., 2021). Subsequently, 2,4-D was evaluated in 1946 and officially introduced in 1948 for controlling broadleaf weeds. Systematic research on weed management in India commenced in 1952 with the launch of the All India Coordinated Research Scheme by the Indian Council of Agricultural Research (ICAR), focusing initially on major crops such as rice, wheat, and sugarcane (Das et al., 2012; Mishra et al., 2021). Over the past four decades, these institutions have generated extensive data on weed surveys, shifts in weed flora, crop-weed competition, yield loss assessments, and various weed management strategies (cultural, chemical, and mechanical), along with herbicide residue analysis in food chains and the environment (Das et al., 2012). In the current era of digital farming and big data, leveraging this wealth of information offers significant potential to enhance future weed management strategies in India.

2.1 Non-chemical practices

Physical, cultural, and organic weed management practices constitute long-standing, environmentally sustainable alternatives to chemical control. Physical methods such as hand weeding, hoeing, burning, flooding, mulching, and soil solarization have been used since the origin of agriculture, with major historical shifts from manual to animal-powered weeding in the 18th century and later to herbicide-based control in the 20th century,

TABLE 3 Current weed control tools in India with their advantages, disadvantages, and efficacy*.

| Sl. no. | Method | Advantages | Disadvantages | Efficacy in indian farming context |
|---------|---|---|---|---|
| 1. | Physical Methods (e.g., hand weeding, hoeing, spading, digging, sickling, burning, flooding, soil solarization, and mulching) | Low-cost for small farms, eco-friendly, immediate weed removal, and suitable for organic farming. Mulching and Soil Solarization can conserve soil moisture, improves soil temperature and fertility, effective against invasive and difficult weeds (e.g., <i>Parthenium</i> , <i>Cyperus</i>). | Labor intensive, time consuming, inefficient for large scale farms, increasing labor costs. High cost for artificial mulches, requires plastic disposal management, solarization less effective in cooler climates, costly for food grains. | Highly effective for smallholder farms, still widely practiced in states with high labor availability. Limited scalability for commercial farming systems due to labor shortages and costs. Effective in high-value horticultural and vegetable crops (e.g., turmeric, tomato). Solarization useful in nurseries and polyhouses. Mulching common in North-East and hilly regions using local materials (e.g., straw, leaves). |
| 2. | Cultural Practices (e.g., stale seedbed preparation, intercropping, mulching, crop rotation, use of competitive varieties, adjusting sowing time and spacing, and green manure incorporation) | Enhances soil health, promotes biodiversity, sustainable and eco-friendly, reduces weed seed banks, compatible with organic systems. | Requires good agronomic planning, slower results, effectiveness varies with crop, climate, and region. | Very effective in rainfed and organic farming systems; highly recommended in low-input traditional systems. Farmers using intercropping and crop rotation report fewer weed issues. Requires localized adaptation and extension support. |
| 3. | Chemical Control (herbicides) | Quick and effective, reduces labor needs, suitable for large areas, cost-effective at scale, increasing availability of low dose formulations. | Development of herbicide resistant weeds, environmental and health concerns, risk of residue in food and soil, overdependence may disrupt IWM. | Widely adopted in rice-wheat systems, particularly in Punjab, Haryana, and U.P. Rapid expansion in plantation areas. Resistance to herbicides like isoproturon and metsulfuron is emerging, necessitating integrated strategies. |
| 4. | Organic Weed Control (ecological and preventive) | Environmentally safe, promotes soil biodiversity, no chemical residues, aligns with certification standards, focus on long-term weed seedbank reduction. | Labor-intensive, knowledge-intensive, limited efficacy against aggressive perennial weeds, slower response time. | Crucial for certified organic farms, especially in Sikkim, Uttarakhand, and hill areas. Adoption increasing under Paramparagat Krishi Vikas Yojana (PKVY). Requires government support and capacity building for long-term sustainability. |

*Summarized from available literature, personal communication, practical experience of the authors, and Source: Rao et al., 2020.

significantly enhancing food production and reducing labor dependence (Das et al., 2012; Rao and Chauhan, 2015; Woyessa, 2022; Gatkal et al., 2025). Cultural practices aim to enhance crop competitiveness and suppress weeds through ecological manipulation, including stale seedbeds, crop rotation, intercropping, mulching, competitive varieties, optimized sowing time and spacing, and green manuring, and they remain integral to Integrated Weed Management systems, particularly in India (Bajwa, 2014; Liebman et al., 2016; Rao and Chauhan, 2015). Numerous studies demonstrate their effectiveness across crops, such as reduced weed pressure in finger millet, maize–cowpea intercropping systems, rice, and rainfed cotton, as well as under conservation and minimal tillage systems where non-residual herbicides may be integrated (Chaugule and Khare, 1961; Dubey, 2008; Patil et al., 2013; Gnanasoundari and Somasundaram, 2014; Das et al., 2016; Das and Yaduraju, 2011; Mahto and Sinha, 1980; Aulakh and Mehra, 2006; Yaduraju and Ahuja, 1995). Mulching and soil solarization further contribute to weed suppression by restricting emergence or inducing heat-mediated mortality, with soil solarization being particularly effective against many annual weeds but less so against deep-rooted perennials such as *Sorghum halepense* and *Cyperus rotundus* (Kumar et al., 1993; Bhullar et al., 2015; Kanellou et al., 2023; Wada et al., 2024). In organic agriculture, where weed management remains the most critical constraint, integrated use of cultural, mechanical, and preventive approaches—supported by modern weeders and Harvest Weed Seed Control techniques—forms the backbone of sustainable weed control, underscoring the need for long-term studies on weed seedbank dynamics and flora shifts (Bärberi, 2002; Mishra et al., 2021; Gamage et al., 2023; Kushal et al., 2024).

2.2 Chemical methods

The use of herbicides for weed management is on the rise in modern agriculture (Mesnage et al., 2021; Saikia et al., 2024a, Saikia et al., 2024b) (Figure 1). Globally, herbicides account for approximately 53% of the crop protection market, followed by fungicides (23%), insecticides (17%), and other categories (7%) (Mishra et al., 2021). However, in India, herbicides comprise only about 17% of total pesticide use, significantly lower than insecticides (44%) and fungicides (37%) (Mishra et al., 2021). Although India ranks as the 4th largest producer of crop protection chemicals worldwide, its average pesticide consumption remains relatively low (less than 500 g/ha, compared to 10–12 kg/ha in countries like Japan). Specifically, annual herbicide consumption in India is about 40 g/ha, whereas in several developed countries it ranges from 675 to 1,350 g/ha. Over the past decade, herbicide use in India has been growing rapidly at an annual rate of 15–20% (Mishra et al., 2021). However, the total volume consumed may not increase proportionally, due to the shift from traditional high-dose herbicides to newer, low-dose, high-efficacy formulations (Manalil et al., 2011).

Presently, herbicide use is most prominent in wheat and rice, followed by plantation crops. Herbicide-based weed management is increasingly favored by farmers due to its rapid action, high efficacy, and cost-effectiveness. A wide range of selective and non-selective herbicides are recommended for effective weed management across major crop groups in India (Das et al., 2012; Shukla et al., 2024) (Table 4). For cereal crops such as rice, maize, wheat, and millets, commonly used herbicides include pre-emergence agents like butachlor, pendimethalin, and atrazine, as well as post-emergence

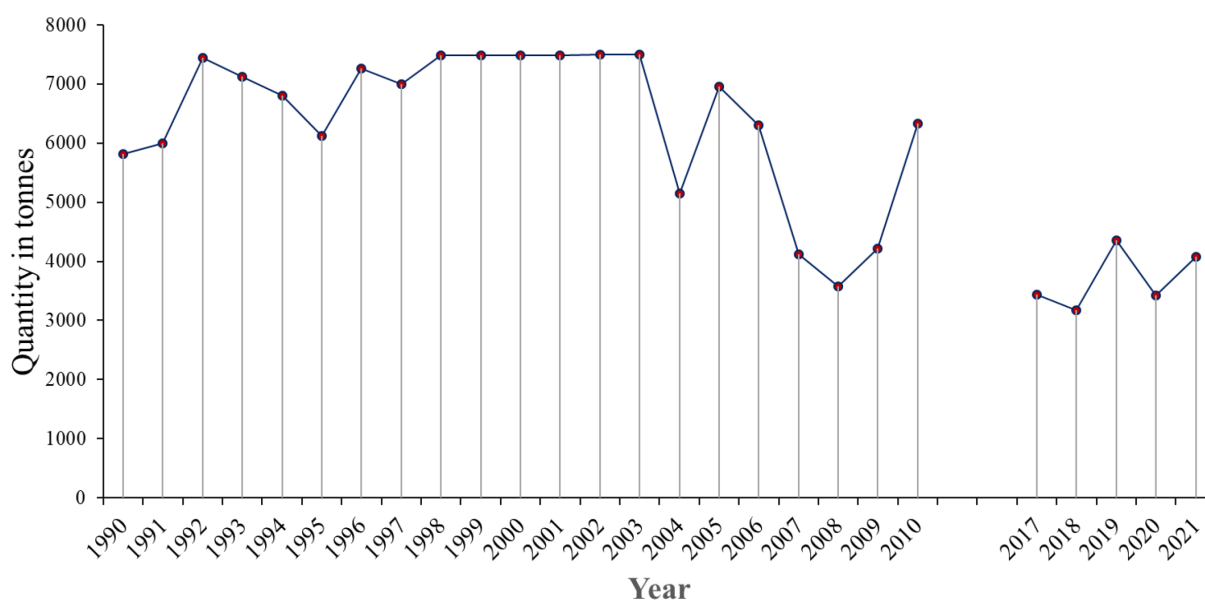


FIGURE 1
Herbicide consumption trend in India (Source: Govt. of India, 2024).

TABLE 4 Recommended herbicides for weed management in various crops in India.

| Category | Crop | Herbicide recommended |
|------------|---|--|
| Cereals | Direct-seeded upland rice | 2,4-DEE, Azimsulfuron, Bispyribac-Na, Cyhalofop-butyl, Ethoxysulfuron, Fenoxaprop-p-ethyl, Oxadiargyl, Oxyfluorfen, Metsulfuron-methyl+Chlorimuron-p-ethyl, Pendimethalin, Pretilachlor, Pyrazosulfuron-p-ethyl |
| | Direct-seeded puddled and transplanted rice | 2,4-DEE, Azimsulfuron, Bispyribac-Na, Cyhalofop-butyl, Ethoxysulfuron, Fenoxaprop-p-ethyl, Oxadiargyl, Oxyfluorfen, Metsulfuron-methyl+Chlorimuron-p-ethyl, Pendimethalin, Pretilachlor, Pyrazosulfuron-p-ethyl |
| | Maize/sorghum/pearl millet | 2,4-DEE, Atrazine, Atrazine + Pendimethalin, Halosulfuron (only for maize), Pendimethalin, Tembotrione, Tembotrione + Atrazine, Topramezone |
| | Wheat | 2,4-DEE, Carfentrazone-p-ethyl, Clodinafop-propargyl, Isoproturon, metsulfuron-methyl, Pendimethalin, Sulfosulfuron, Sulfosulfuron + metsulfuron-methyl, Metsulfuron-methyl + Iodosulfuron methyl, Clodinafop-propargyl + Metsulfuron-methyl |
| Millets | Sorghum/pearl millet | 2,4-DEE, Atrazine, Pendimethalin |
| Pulses | Pigeonpea/blackgram/greengram | Imazethapyr, Pendimethalin, Oxadiazon (not for green gram), Oxyfluorfen (not for green gram), Quizalofop-ethyl |
| | Soybean | Chorimuron, Clomazone, Fenoxaprop-p-ethyl, Fenoxaprop-p-ethyl + Chlorimuron-ethyl, Imazethapyr, Imazethapyr + Imazomox, Metribuzin, Oxadiazon, Pendimethalin, Quizalofop-ethyl, Quizalofop-ethyl+ Chlorimuron-ethyl |
| | Chickpea/lentil/pea | Chlorimuron-ethyl, Metribuzin, Oxyfluorfen, Pendimethalin, Quizalofop-ethyl |
| Oilseeds | Groundnut/sunflower | Imazethapyr (only for groundnut), Pendimethalin, Oxadiazon, Oxyfluorfen, Quizalofop-ethyl |
| | Rapeseed & mustard | Isoproturon, Pendimethalin, Oxadiazon, Quizalofop-ethyl |
| Fibre crop | Cotton | Alachlor, Diuron, Glyphosate, Paraquat, Pendimethalin, Pyriithiobac Sodium, Quizalofop-ethyl |
| Vegetables | Tomato/Brinjal | Alachlor, Metribuzin (in tomato only), Pendimethalin |
| | Cabbage/cauliflower/knolkhol | Pendimethalin |
| | Potato | Isoproturon, Metribuzin, Paraquat (up to 2% sprouting), Pendimethalin |
| | Onion/garlic | Alachlor, Pendimethalin, Oxyfluorfen |
| | Beet/radish/carrot | Pendimethalin |
| Sugar crop | Sugarcane | 2,4-DEE, Ametryne, Atrazine, Glyphosate, Halosulfuron, Metribuzin, Paraquat |

*Source: Rao et al., 2020; Mishra et al., 2016; Das et al., 2012.

options such as bispyribac-sodium, 2,4-D, and metsulfuron-methyl, tailored to crop and field conditions (e.g., direct-seeded vs. transplanted rice). In pulse crops like soybean, pigeonpea, and chickpea, herbicides such as fluchloralin, imazethapyr, and pendimethalin are widely used, often in combination or sequence for season-long control. The selection and application of herbicides are crop-specific and depend on weed flora, cropping system, and regional agronomic practices. Integrating these herbicides into crop-specific weed management plans ensures higher efficacy, reduced crop-weed competition, and improved yields.

3 Agricultural and economic consequences of the lack of HT crops in India

Indian agriculture presents a complex range of opportunities and challenges in the absence of HT crops, which have a significant impact on crop yields, labor costs, herbicide consumption, weed management techniques, and sustainable agricultural practices

(Parven et al., 2024). Manual weeding and the application of non-selective herbicides are two pillars of traditional weed management techniques in India that are labor-intensive, time-consuming, and frequently ineffective, particularly in large-scale or mechanized farming systems. The issue is exacerbated by labor shortages during peak farming seasons, which increase production costs and reduce farmer profitability (Nath et al., 2024). Weed infestation is not controlled in a crop/cropping system right away; it drastically lowers productivity and quality in crops like rice, where transplanting is prevalent. Direct-seeded rice (DSR), a conservation agriculture technique that can conserve water and lower greenhouse gas emissions, is also less common due to the absence of HT crops. Compounding the issue, non-HT systems that rely too heavily on a limited selection of herbicides may eventually cause weeds to develop herbicide resistance (Bajwa, 2014; Kaur et al., 2024).

Indian farmers encounter considerable difficulties in efficiently controlling weeds since HT crop options are not readily available (Nath et al., 2024). As a result of ineffective weed management methods, agricultural yields decrease, input prices rise, and

environmental pressure increases (Bajwa, 2014; Barman et al., 2014). Because weeds fiercely fight with crops for light, water, and nutrients, yield losses are estimated to be between 25 and 26 per cent during the *kharif* season and 18 to 25 per cent during the *rabi* season (Mishra and Choudhary, 2025). This amounts to an annual loss of about ₹92,000 crore (USD 11 billion) (Anonymous, 2024a). Farmers' finances are further strained by the ₹3,700 to ₹7,900 per acre that they must spend on weed treatment. The necessity of technology-based weed management is shown by a study conducted by the Federation of Seed Industry of India (FSII), which covered 30 districts and seven important crops such as rice, wheat, maize, cotton, sugarcane, soybean, and mustard. The emergence of weeds that are resistant to herbicides and the constant competition for resources make control efforts more costly and challenging (Chinnusamy et al., 2014; Anonymous, 2024b).

Nations like the United States, Canada, Brazil, and China have widely embraced genetically modified (GM) crops that are resistant to herbicides (Cheng et al., 2024). For instance, HT cultivars account for more than 90% of the soybean and maize grown in the USA and Brazil, enabling effective, large-scale weed control with little labor. These nations report higher overall output, less soil disturbance from conservation tillage, and significant cost reductions in weed control. Higher yields and profitability have been greatly enhanced by HT canola in Canada, whereas hybrid rice with HT characteristics has increased efficiency and decreased chemical load in some areas of China (Cheng et al., 2024; Geddes et al., 2022).

India is at a competitive disadvantage in comparison to these countries due to its limited adoption of HT crops (just recently released non-GM HT rice), which results in higher input costs and lost potential yield improvements. Indian farmers are thus losing out on economic opportunities that farmers in other nations are already taking advantage of, in addition to productivity, when they do not have access to HT crops (Verma et al., 2015). The opposition by the anti-GM lobby and the spread of misinformation have been significant factors in the long delay of GM crop commercialization in India. Environmental groups, farmer organizations, and prominent activists have raised public fears about biosafety, ecological harm, and economic dependence on multinational seed companies, contributing to a cautious regulatory environment and public scepticism toward GM technology. Certain scientific reports and opinions are seemingly legit and add fuels to these debates (Lather, 2024; Kuruganti, 2011). Indian scientists and policymakers have noted that such opposition often amplifies unfounded fears and misinformation about GM crops' safety and impacts, hindering broader acceptance and slowing policy decisions on commercial releases beyond Bt cotton (Jayaraman, 2017; Sreevastha, 2025).

4 Availability of HT crops in Indian Market

The illegal imports and marketing of HT seeds are a significant concern in the absence of licensed HT crops. There is a flourishing black market for HT cotton seeds despite the prohibition on

unapproved GM crops, particularly in states that produce a lot of cotton (Balasubramani et al., 2021). The sale of these illicit seeds has reportedly increased significantly, which raises concerns about the uncontrolled use of glyphosate and possible environmental damage. Because such cultivation evades governmental oversight, it is challenging to adequately address health and environmental hazards (Rao et al., 2020). Herbicide-resistant weeds could appear if adequate stewardship isn't practiced, making weed control more difficult and requiring more chemical herbicides (Monosson, 2015). In addition to undermining the regulatory framework, this illicit trade puts farmers at risk since they might not be aware of the dangers associated with using unlicensed seeds. Without HT crops, reliance on herbicide-only systems may remain low, potentially improving environmental safety as several environmental problems, including deteriorating soil health, water pollution, and decreased biodiversity, have been connected to the overuse of HT crops and glyphosate (Yaduraju, 2021; Anonymous, 2021).

5 Unique weed management keys in India reducing reliance on HT crops

5.1 Integrated weed management as national strategy

India's weed control approach is anchored in the IWM framework promoted by the ICAR and State Agricultural Universities (SAUs). This strategy combines traditional, cultural, mechanical, and to a limited extent, selective chemical methods, focusing on prevention, competition, and physical removal. Key components of the IWM followed regularly in India include:

Preventive measures: Clean cultivation, use of clean seeds, keeping the seed bed free from weeds, using well decomposed organic manures, keeping the bunds and irrigation channels free from weeds, keeping tools and farm machinery clean and control of weeds before they attain reproductive stage are some of the basic and free of cost practices to be followed for successful cultivation of any crop.

Tillage: Before sowing, deep or shallow tilling destroys existing weeds and can bury weed seeds deep in the soil from where they can't germinate, or, conversely, bring them to the surface to be dried out and killed.

Cultural methods: Crop rotation, timely sowing, stale seedbed techniques, and intercropping and mixed cropping that creates a dense canopy that shades the soil, suppressing weed growth by limiting light availability. In stale seedbed, the field is prepared, and a light irrigation is given to stimulate the first flush of weed seeds to germinate. These seedlings are then destroyed (usually by shallow tillage or a non-selective herbicide) before the main crop is sown, allowing the crop to germinate in a relatively weed-free environment.

Optimum planting density and sowing time: Using high-quality, weed-free seeds and ensuring optimal planting density allows the crop canopy to close quickly, shading out young weeds. Adjusting the time of sowing can also allow the crop to

establish a competitive advantage before the major weed flushes occur.

Mechanical and manual control: Regular inter-row hoeing and hand weeding remain widespread, especially in smallholder systems. While labor-intensive, it's highly effective for removing weeds both between and within crop rows.

Example: In rice-wheat systems, ICAR promotes stale seedbed technique and zero tillage with pre-sowing irrigation followed by shallow tillage or herbicide application to kill weed flushes before planting.

5.2 Mechanization and smart implements

India is rapidly mechanizing weed control, particularly through custom hiring centers and farm machinery banks supported by government programs like Sub-Mission on Agricultural Mechanization (SMAM). Tools and technologies in this program include power weeders and brush cutters for vegetable and pulse crops, cono weeders and rotary weeders in direct-seeded and transplanted rice, inter-row cultivators, finger weeders, and sensor-guided hoes in row crops such as maize, soybean, and cotton, drones and precision sprayers being tested by ICAR for site-specific herbicide application, minimizing drift and dosage.

5.3 Use of cover crops and mulching

To suppress weeds without herbicide-tolerant crops, cover crops like cowpea, sunn hemp (*Crotalaria juncea*), and dhaincha (*Sesbania aculeata*) are integrated between rotations and organic mulches (e.g., straw, sugarcane trash, or biodegradable films) are used to prevent weed emergence, especially in horticultural and conservation agriculture systems.

5.4 Biological and bioherbicidal approaches

India is actively exploring eco-friendly alternatives through public research.

Bioherbicides: Fungal pathogens (*Colletotrichum gloeosporioides*, *Phoma herbarum*, *Sclerotium rolfsii*) tested against *Parthenium* and *Eichhornia*. Microbial consortia and plant extracts are maintained under ICAR- NBAIM (National Bureau of Agriculturally Important Microorganisms) and NIPHM (National Institute of Plant Health Management) programs for selective weed inhibition.

Allelopathic crops: Use of sorghum, mustard, and rice genotypes with natural allelochemical release to suppress weeds.

5.5 Chemical herbicides

Even without HT crops, India relies on selective pre- and post-emergence herbicides that are compatible with conventional crop

varieties. Weed control programs in India largely depends on pre-emergence herbicides such as pendimethalin, oxyfluorfen, butachlor, and pretilachlor. Post-emergence herbicides are selected primarily based on selectivity and natural tolerance of the crops, not contingent upon the HT cultivars (Table 4). For example, quizalofop-ethyl is applied to control various annual and perennial grass weeds in only broadleaf crops like cotton, soybeans, and other pulses; bispyribac-sodium is applied in rice at young seedling stage to avoid injury; and tembotrione is applied in maize as it is naturally tolerant. Moreover, tank mixtures and sequential applications are optimized to manage resistant or mixed weed flora. Emphasis is placed on rotating herbicide modes of action to delay resistance.

5.6 Community-based weed management programs

Programs like Farmer Field Schools (FFS), group-based weeding in transplanted rice and cotton, awareness campaigns against illegal use of HT cotton (which is informally present in some states like Maharashtra, Gujarat, and Telangana), etcetera run by Krishi Vigyan Kendras (KVKs) under ICAR and NGOs demonstrate cost-effective IWM practices.

5.7 Policy and extension support

National Agricultural Innovation Project (NAIP) and National Innovations in Climate Resilient Agriculture (NICRA) projects include weed management as a resilience measure. India Society of Weed Science (ISWS) coordinates nationwide weed scientists to conduct research on resistance, weed shifts, and eco-friendly management strategies. These units advise and support the weed management policy decisions and necessary interventions from central government time to time to uphold a robust crop management program in such a big country.

6 Does India need HT crops?

In India, increasing labor shortages and rising wage levels have diminished the economic feasibility of manual weeding (Devi, 2011; ICFA, 2017), leading to a growing reliance on chemical-intensive weed management systems (Figure 1), where pesticide consumption has remained relatively stable at approximately 55–69 metric tonnes annually (GOI Statistical Database, 2024), yet herbicide use has expanded more rapidly than that of insecticides and fungicides, registering an annual growth rate of 6–8% and achieving the fastest growth rate in the recent past.

Herbicide Tolerant (HT) crops, engineered to withstand specific herbicides, offer a potential solution by enabling precise weed control, simplifying management, reducing manual labor needs, enhancing productivity and profitability for farmers, and supporting sustainable practices like reduced tillage (Sekhar et al., 2024; Lee et al., 2014), with studies indicating that HT cotton can

significantly cut labor costs for weed control, yielding monetary benefits (Mehta, 2019), while in DSR, where weed management is a major hurdle and manual weeding labor-intensive, HT rice varieties are being explored as an effective option, potentially reducing labor costs by up to 40% (Chaudhary et al., 2023). Non-GM HT varieties like Pusa Basmati 1979, 1985, and CR Dhan 807 already prove viable, and illegal farmer adoption of HT-Bt cotton on 20% of acreage signals desperate demand, particularly for mustard hybrids like DMH-11 to slash edible oil imports, yet widespread adoption hinges on navigating ecological, socio-economic, and regulatory hurdles, including risks of herbicide-resistant “superweeds,” potential environmental and health impacts from increased herbicide use, and socio-economic consequences like rural labor displacement, high seed costs, and seed sovereignty erosion (Ofosu et al., 2023; Sadikiel Mmbando, 2024). Political interference by environmental NGOs (ENGOs) has stalled GM commercialization through misinformation campaigns, imposing staggering costs in lost yields, health impacts, and lives - Bt Brinjal faced a moratorium in February 2010, unresolved after 16 years despite scientific backing, and while GEAC approved GM mustard (DMH-11) in May 2017, government clearance lingers amid debates, shifting focus from brinjal but echoing the same impasse, with public skepticism fueled by unproven fears delaying innovations despite Bt cotton’s proven success since 2002. India needs HT crops selectively, prioritizing stewardship through herbicide rotation, integrated weed management, and smallholder subsidies - favoring non-GM HT for rice and cotton, and GM for mustard and soybean where gaps are acute to enhance profitability without monocultures; regulatory reforms must sideline ENGO misinformation, emphasizing data-driven approvals like GEAC’s, as with labor costs soaring and water woes mounting, rigorously tested HT integration for ecology and equity bolsters resilience, and rejecting them outright forfeits gains, ensuring a nuanced strategy delivers sustainable prosperity for India’s 146 million farmers.

7 Status of research and adoption of HT crops in India

HT cultivars are designed to tolerate specific broad-spectrum herbicides, allowing weeds to be killed while leaving the cultivated crop intact. These crops can be classified into non-transgenic (developed through conventional breeding methods like selection or mutation breeding for resistance traits) and transgenic (genetically engineered). Currently, transgenic or GM HT crops face strict regulatory norms in most countries and are banned for cultivation in many regions. In contrast, non-GM HT crops are widely accepted globally due to fewer regulatory hurdles. In India, the Genetic Engineering Appraisal Committee (GEAC) under the Ministry of Environment, Forest and Climate Change (MoEF&CC) permits only GM cotton for cultivation, making it the sole approved GM crop in the country.

Transgenic cotton in India primarily involves two types: “insecticidal” (Bt cotton) that has inbuilt protection against insects, and “herbicide tolerant Bt cotton” (HT-Bt cotton) that has inbuilt

protection against glyphosate. While Bt cotton cultivation is legal, HT-Bt cotton remains unauthorized in India despite its adoption in other countries. A 2018 government report by a high-level committee revealed that ~15% of India’s cotton crop cultivated in states like Maharashtra, Telangana, Andhra Pradesh, and Gujarat might involve non-regulatory HT-Bt varieties. This highlights the regulatory challenges in controlling unapproved genetically modified crops. Recently, Bayer sought regulatory approval for Bollgard II Roundup Ready Flex (BG-II RRF) in India, a genetically engineered variety combining herbicide tolerance and insect resistance. If approved by the Genetic Engineering Appraisal Committee (GEAC), this could formalize the cultivation of HT-Bt cotton, potentially addressing widespread illegal use while introducing stricter regulatory oversight (ISAAA, 2022).

The Government of India recently approved the environmental release of GM mustard hybrid DMH-11 and its parental lines during the 147th meeting of the Genetic Engineering Appraisal Committee (GEAC) on October 18, 2022. This approval permitted seed production and testing under existing ICAR guidelines, marking a significant policy shift after a decade-long moratorium on GM crops. Developed by the Centre for Genetic Manipulation of Crop Plants (CGMCP) at the University of Delhi South Campus, the GM mustard hybrid DMH-11 uses the *barnase-barstar* system to create two parental lines: Varuna bn 3.6 (MS line) and EH-2 modbs 2.99 (RF line). Importantly, DMH-11 is not classified as an HT crop despite containing the *bar* gene, which confers resistance to the herbicide phosphinothricin (glufosinate-ammonium). The government clarified that phosphinothricin use is neither permitted nor required in farmers’ fields. Its application is restricted to hybrid seed production plots, where the herbicide ensures purity by eliminating non-hybrid plants during breeding (PIB Delhi, 2023).

Till 2021, HT rice varieties were not available in India, though countries like the U.S. had released varieties such as Liberty Link, Provisia, Clearfield, and Jietian. In 2021, the Indian Agricultural Research Institute (IARI) introduced India’s first non-GM herbicide-tolerant ‘RobiNOweed’ Basmati rice varieties - ‘Pusa Basmati 1979’ and ‘Pusa Basmati 1985’, developed by backcrossing popular varieties Pusa 1121 and Pusa 1509 with Robin, incorporating a mutated acetolactate synthase (ALS) gene to enable farmers to spray Imazethapyr 10% SL herbicide for weed control (Table 5). The ICAR-National Rice Research Institute, Cuttack further transferred this gene to four non-basmati varieties - Sahbhagidhan (upland), Naveen (favorable uplands/irrigated), Swarna Sub1, and Pooja (shallow lowlands). The HT line of Sahbhagidhan has been released as ‘CR Dhan 807’ which is the first non-GM HT non-basmati rice released in 2023. Concurrently, the joint venture ‘Paryan’ established by American company RiceTec (via subsidiary Savannah Seeds) and India’s Mahyco developed hybrid rice varieties ‘Sava 134’ and ‘Sava 127’, and wheat varieties ‘Goal’ and ‘Mukut’, all engineered with a mutated ALS gene to tolerate Imazethapyr. Weeds can be destroyed by spraying Imazethapyr 25 days after sowing these rice varieties through DSR and wheat varieties through zero tillage, but the rice and wheat crops will remain completely protected (Table 5).

TABLE 5 Status of herbicide tolerant (HT) cultivars in major crops in India.

| HT crops | Status | Variety released | Reference |
|----------|--|----------------------------|--------------------|
| Rice | Indian Agricultural Research Institute (IARI) has released India's first non-GM herbicide-tolerant basmati rice varieties in 2021 | Pusa Basmati 1979 and 1985 | Kar et al. (2024) |
| Rice | National Rice Research Institute (Cuttack) has released India's first non-GM herbicide-tolerant non-basmati rice in 2023 | CR Dhan 807 | Kar et al. (2024) |
| Rice | Joint venture 'Paryan' established by American company RiceTec (via subsidiary Savannah Seeds) and India's Mahyco developed hybrid rice varieties. RiceTec's proprietary technology 'FullPage' will be used for DSR | Sava 134 and Sava 127 | Rural Voice (2024) |
| Wheat | Joint venture 'Paryan' established by American company RiceTec (via subsidiary Savannah Seeds) and India's Mahyco developed wheat varieties. The 'FreeHit' Cropping Solution developed by Mahyco in collaboration with the US company Geneshifters will be used for zero tillage | Goal and Mukut | Rural Voice (2024) |
| Maize | Trials are going on by the states of Haryana and Karnataka after approvals from the GEAC for GM stacked maize (MLS10101 x MLS13621) | – | ISAAA (2022) |
| Cotton | HT-Bt cotton remains unauthorized in India despite its adoption in other countries. However, trials are going on by the states of Haryana and Karnataka after approvals from the GEAC for GM stacked cotton hybrids (MLS2154 x MLS4301 x MLS2531, and MLS2154 x MLS4301) | – | ISAAA (2022) |
| Mustard | The Government has approved the environmental release of Genetically Modified (GM) Mustard hybrid DMH-11 and its parental lines during 147 th meeting of Genetic Engineering Appraisal Committee (GEAC) on 18 October, 2022 for its seed production and testing as per existing ICAR guidelines, conditions imposed by the GEAC while recommending the environmental release of GM mustard hybrid DMH-11 and its parental lines; and other extant rules/regulations prior to commercial release | – | PIB Delhi (2023) |

Further, confined field trials of GM HT crops are underway in India after approvals from the GEAC under the MoEF&CC. For instance, cotton and maize have been approved for such trials by the states of Haryana and Karnataka, and following receipt of No Objection Certificates (NOCs) from these state governments, the GEAC cleared proposals from Rallis India Limited to conduct BRL-1 (first and second year) field trials of two GM stacked cotton hybrids (MLS2154 x MLS4301 x MLS2531, and MLS2154 x MLS4301) and GM stacked maize (MLS10101 x MLS13621). These trials, aimed at evaluating both pest resistance and tolerance to glyphosate herbicide, are expected to advance research on herbicide tolerance in India (ISAAA, 2022).

HT crops are poised to substantially impact weed management practices, particularly by addressing labor shortages and rising agricultural wages, which may drive greater farmer acceptance of herbicide-based solutions. By simplifying weed control through targeted herbicide use, HRCs offer significant potential to streamline agricultural practices if managed judiciously, while also promoting environmental benefits such as no-till farming, which reduces soil erosion and conserves moisture. However, this technology carries risks: it could escalate cultivation costs due to monopolization of the seed-agrochemical market and accelerate the evolution of herbicide-resistant weeds, threatening long-term crop productivity and sustainability. Balancing these advantages and challenges will require careful regulatory oversight and integrated pest management strategies.

8 Emerging herbicide resistance in Indian agriculture

Heavy reliance on a single herbicide or herbicides with the same mode of action can drive the evolution of resistance and shift weed populations toward hard-to-manage species. In India, for instance, widespread use of the substituted phenyl urea herbicide isoproturon led to resistance in *Phalaris minor*, sharply reducing wheat yields in impacted regions (Bhullar et al., 2017) (Table 6). Natural weed populations contain individuals with inherent mechanisms to survive specific herbicides; repeated applications create selection pressure that boosts the proportion of resistant plants over time. The emergence of isoproturon resistance in *P. minor* in Haryana represented India's first case of herbicide resistance and the world's first documented instance of weed resistance to isoproturon. Since then, in India, multiple cases of herbicide resistance have been recorded: (i) *Phalaris minor* has developed resistance to PSII, ACCase, and ALS inhibitors (Chhokar et al., 2015), (ii) *Rumex dentatus* shows resistance to metsulfuron (ALS inhibitor) and cross-resistance to mesosulfuron + iodosulfuron, pyroxsulam, and halauxifen + florasulam (Chhokar et al., 2015), (iii) *Polypogon monspeliensis* is resistant to sulfosulfuron, mesosulfuron, and pyroxasulam, (iv) In soybean, *Echinochloa colona* and *Commelina communis* have developed resistance to imazethapyr (ALS inhibitor) (Chander et al., 2019), and (v) In rice, *Echinochloa crusgalli* and *Cyperus difformis* have become resistant to

TABLE 6 Reports of herbicide resistance cases in weeds from India.

| Weed species | Crop/system | Herbicide resistance | States reported | Reference |
|---|--------------------|---|--|--|
| <i>Phalaris minor</i> (little seed canary grass) | Wheat (rice-wheat) | Resistance to isoproturon; later multiple resistance to ACCase and ALS inhibitors | Punjab, Haryana, W. Uttar Pradesh, Rajasthan | Malik and Singh, 1995; Chhokar and Malik, 2002 |
| <i>Rumex dentatus</i> (toothed dock) | Wheat | Resistance to metsulfuron-methyl (ALS inhibitor) | Haryana, Punjab, W. Uttar Pradesh | Chhokar et al., 2013 |
| <i>Chenopodium album</i> (lamb's quarters) | Wheat | Resistance to metsulfuron-methyl (ALS inhibitor) | Punjab, Haryana | Chhokar et al., 2013 |
| <i>Avena ludoviciana</i> (wild oat) | Wheat | Resistance to ALS inhibitors; reduced sensitivity to ACCase inhibitors | Punjab, Haryana, Rajasthan | Chhokar et al., 2012 |
| <i>Polypogon monspeliensis</i> (rabbitfoot grass) | Wheat | Resistance to sulfosulfuron/mesosulfuron (ALS inhibitors) | Punjab, Haryana | Chhokar et al., 2015 |
| <i>Cyperus difformis</i> (smallflower umbrella sedge) | Rice | Reduced sensitivity/resistance to bispyribac-sodium (ALS inhibitor) | Tamil Nadu, Kerala, Andhra Pradesh | Rao et al., 2017 |
| <i>Echinochloa crus-galli</i> (barnyardgrass) | Rice | Confirmed resistance to bispyribac-sodium (ALS inhibitor) | Chhattisgarh, Kerala | Choudhary et al., 2023 |

Bispyribac-Na (ALS inhibitor). As herbicide-based weed control continues to dominate weed management strategies in India, the prevalence of herbicide-resistant weeds in farmers' fields poses a serious challenge (Nath et al., 2024). Key strategies to prevent shifts in weed flora and resistance development include herbicide rotation and the use of herbicide mixtures. Thus, a deep understanding of resistance mechanisms, coupled with integrated weed management practices, is essential to delay resistance evolution and sustain herbicide effectiveness.

Despite present issues, India's herbicide resistance issue is yet less concerning than that of western nations. This is primarily because, in contrast to western nations, India's agricultural systems use very few herbicides in overall low volume. Lower treatment rates minimize the overall selection pressure for resistance, even if some weed populations across multiple species in the rice-wheat cropping system have become resistant in Pakistan, Sri Lanka, and India. Additionally, the Indian government promotes integrated weed management techniques and the prudent use of herbicides.

TABLE 7 Historical events in Indian agriculture in herbicide tolerant (HT) issues.

| Year/Period | Event | Details |
|----------------|---|---|
| 1960s–1980s | Green revolution and chemical herbicide adoption | High-yielding rice and wheat, mechanization, and rising labor costs led to widespread adoption of herbicides (pre-HT era). |
| 1980s–1990s | Rise of herbicide dependence in wheat (isoproturon use) | Continuous use of isoproturon in wheat led to first documented herbicide resistance in <i>Phalaris minor</i> (little seed canary grass) in Punjab and Haryana ~1992–93 (Malik and Singh, 1995). |
| 1990s–2000s | Multiple resistance in wheat weeds | <i>Phalaris minor</i> developed multiple resistance (PSII, ACCase, ALS) to herbicides including isoproturon, clodinafop, fenoxaprop, sulfosulfuron, mesosulfuron and pinoxaden. Other species like <i>Rumex dentatus</i> , <i>Chenopodium album</i> , <i>Avena ludoviciana</i> , and <i>Polypogon monspeliensis</i> showed resistance to ALS inhibitors and other chemistries (Chhokar and Sharma, 2008). |
| 2000s–2010s | Bt cotton adoption; continued debate on HT crops | Indian farmers widely adopted Bt cotton (insect-resistant) but genetically engineered HT crops were not officially approved; unregulated HT seeds circulated illegally without biosafety approval (Arya, 2025). |
| 2010s–2020s | Labor scarcity and shift to DSR in rice | DSR adoption rose in Punjab and Haryana to combat labor shortages and water scarcity; herbicide use intensified for early weed flush control. |
| 2021 | Release of first non-GM herbicide-tolerant rice varieties | Indian Agricultural Research Institute (IARI) released non-GM HT rice (e.g., Pusa Basmati 1979 and 1985) tolerant to imazethapyr, enabling selective weed control in DSR systems (Damodaran, 2021). |
| 2024 | Commercial cultivation of HT rice begins | HT rice varieties released for commercial cultivation to address weed pressure, labor and water issues in NW India (Mohan, 2024). |
| 2020s (Policy) | Regulatory action on herbicides | Several Indian states and national policy discussions moved to restrict glyphosate use in agriculture, permitting certified application due to safety concerns (though not entirely banned (PTI, 2022)). |

However, this current advantage may eventually fade away due to growing labor shortages and an increased reliance on herbicides (Bhullar et al., 2017; Verma et al., 2015; Kaur et al., 2024).

Historical account of events shows that India has been cautious and circumspect in approaching to HT technologies while developing its own non-GMO HT crops (Table 7). Recent restrictions on glyphosate use in agriculture, permitting only certified application due to safety concerns (though not entirely banned), while releasing non-GMO HT rice varieties for commercial cultivation in 2024 to address weed pressure are some of the careful steps for example.

9 Conclusion

Given the compounding population growth rate and increasing food demand, India needs to find out a clear and strategic roadmap for achieving its food production goal. Increasing cost of cultivation using manual labor is no longer a viable solution for a country like India that transitioning from an agriculture-based to an industry and service-leaning country. At this juncture, India needs to embrace the technological advancements in crop cultivation in order to improve production efficiency. It is evident that scaling up HT crop cultivation in India will skyrocket the herbicide uses in Indian agriculture, cause temporary disorientation in human resources involved in agricultural sector and result in several unforeseen sociopolitical issues. It may cause unprecedented consequences on soil, environment, and water streams. Herbicide residues in the soil can affect non-target organisms, and runoff into streams, rivers, and other water bodies can harm aquatic ecosystems and potentially impact drinking water sources. The more efficient weed control offered by HTCs can reduce plant biodiversity in agricultural fields, which in turn affects the insects and other wildlife that rely on those plants for food and habitat. However, several western countries embraced this technological advancement long ago and have been able to stabilize environmental and social issues. India must be prepared to embrace the global growth rate in agricultural sciences while developing its strategic stewardship for tackling the associated consequences of HT upscaling.

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