

Exploring alternatives for assessing and improving herbicide use in intensive agroecosystems of South Asia: A review

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Abstract: Weeds pose a serious threat in achieving sustainable and profitable crop production. South Asia, as both a major food-producing and consuming region, needs a linear increase in food grain production. Among the several methods of weed management practice, herbicides are the most cost-effective and timely solution. Rice and wheat are the major staple food crops and the introduction of low-dose high efficacious herbicides, such as pyrazosulfuron-ethyl and sulfosulfuron in rice and wheat, respectively, have the major share in the region. With the continuous use of similar herbicides or application of a limited number of herbicides with a similar mode of action in intensive cropping systems, the evolution of herbicide resistance in many weeds has become a serious concern. With limited

options of alternate herbicides, the evolution of cross and multiple resistance has emerged as a major challenge. This review has highlighted the usage of herbicides in South Asian countries, the development of herbicide resistance in major crops of the region, and the possible solutions. The adoption of site-specific integrated weed management in managing both herbicide resistance and weed menace, and location-specific agronomic interventions remains critical. The immense potential of adopting novel technologies, such as the use of economic sensing devices for real-time weed identification and spot-spraying, and early detection of herbicide resistance in weeds and their phenotypes, might offer alternatives of herbicide use for safer and cleaner economies.

Keywords: Crop-competitiveness; herbicide consumption; herbicide resistance; integrated weed management; weed phenotyping

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1. Introduction

The United Nations project 60% of the global population will be found in Asia, particularly in India and China by 2050. To meet the projected demand for food and feed in these countries, an enormous dependence on agrochemicals is expected. Weeds as a biotic threat have the most deleterious impact on crops worldwide. Besides offering direct inter-specific competition for natural and applied resources, weeds cause a significant decline in the produce and quality of agricultural systems. In India alone, an annual loss of more than USD 11 billion is estimated due to weeds in the 10 major crops (Gharde et al., 2018). Distinctive traits of weeds like acclimatization, adaptation, and plasticity make them highly competitive with crops. Globally, the herbicide sector has accounted for USD 43.8 billion or 52% of the total pesticide market as the largest segment during 2019 (Sharma et al., 2019). It is expected to be the fastest-growing segment at a growth rate of 12.8% from 2020-2025 (Sharma et al., 2019). The top 10 pesticide usage countries in the world are China, the USA, Argentina, Thailand, Brazil, Italy, France, Canada, Japan, and India (Pariona, 2018). Moreover, it has been estimated that by the year 2025, global pesticide usage will increase up to 3.5 million tonnes (Zhang, 2018). Presently, the global usage of pesticides is approximately 2 million tonnes, out of which 47.5% are herbicides, 29.5% are insecticides, 17.5% are fungicides, and 5.5% are other pesticides (Sharma et al., 2019). The amount of herbicides used during the year 2019 in India, Bangladesh, Sri Lanka, Pakistan, and Nepal was around 9,749, 1,195, 716, 245, and 164 tonnes, respectively (Food and Agriculture Organization, 2020).

Chemical weed management is a feasible, highly economic, and effective method of weed control, but over-reliance on herbicides has led to serious-environmental concerns, and thus, focusing on alternative methods becomes imperative. The evolution of resistance among the noxious weeds against the most popular herbicides has forced the farmers and other stakeholders to consider other ecologically sound best management practices for sustainable weed management. The integration of various tactics of weed management remains of paramount importance. This review highlights updated and comprehensive information of herbicide use, advantages of herbicide use, challenges, and sustainability issues along with alternative weed management

strategies. The prospects and future research are also discussed to address the dire need for the development of integrated herbicide resistance management.

2. Herbicide use in South Asia

Weeds and crops co-exist in the field since time immemorial, but after the popularization of chemical weed management with the advent of a variety of herbicide molecules, alternative methods, such as tillage, manual weeding, crop rotation, etc., have become less common. Out of the total global herbicide consumption, almost 50% has been reported from South Asia (Food and Agriculture Organization, 2019). Herbicides account for almost 16% of the total pesticide market in India and are intensively being used in rice, wheat, and soybean (Bhullar et al., 2017). In 1970, glyphosate was discovered by Franz from Monsanto Company and since 2001, glyphosate has been the most widely used herbicide in HT crops (Beckie et al., 2017). Cotton and paddy are the major crops, which consume almost 50 and 18% of the total herbicide consumption in the world. However, glyphosate and 2,4-D are extensively used herbicides in tea and coffee plantations in South Asia. In India, glyphosate accounts for 37% of the active ingredient of the total herbicides used and almost 24% of it is being used in cereals, cotton, sugarcane, some fruits, and vegetables (Brookes, 2020). In India, glyphosate is being used almost on 12 M ha area with an average use of 0.68 kg/ha. It is an effective and economic solution to the weed problem; thus, an additional total cost of USD 200 million and 23 USD/ha will be incurred globally in the case glyphosate is banned (Brookes, Barfoot, 2018).

3. Challenges in herbicide use in South Asia

Higher wages have accelerated the adoption of chemical weed management in South Asian countries (Rao et al., 2007). Herbicides are known for their cost-effectiveness, higher weed control efficacy, immediate response, and labor-saving. However, longer persistence in the soil-plant-atmosphere continuum and possible harm to the non-target organisms are the major apprehension in their continuous use. Some other challenges in herbicide use in South Asian countries have been mentioned below.

3.1 Limited choice in herbicides use

Rice is cultivated in more than 55% arable area of South Asia and chemical weed management offers an economic solution in rice. The rotation of herbicides with a dissimilar mechanism of action is often recommended for effective weed control and delaying the development of herbicides. The frequency of development of newer herbicides with a different mechanism of action (MOA) and their commercialization till the 1980s was once every 2.5 to 3 years (Jeschke, 2015). Thereafter, no new MOA have been

introduced. New herbicides with prevailing MOA could be used only where cross-resistance has not been reported so far (Jeschke, 2015). The increasing cases of the evolution of resistance in common herbicides indicate that most of the herbicides might become unusable in the coming times. The new HT crops are resistant to old herbicides like 2,4-D and the limited choice of new herbicides leaves farmers with no option.

3.2 Over-reliance on use of glyphosate

Glyphosate as a broad-spectrum herbicide with a new MOA was promoted as a miracle herbicide, especially after the popularity of transgenic crops, and now it has become the most widely used herbicide for weed control in both agricultural and non-agricultural areas over the past 30 years (Andert et al., 2019). The worldwide annual usage and production is more than 0.8 million t and 1.1 million t, respectively. Glyphosate represents 12% of the overall pesticide market globally (Székács, Darvas, 2018). Glyphosate is one of the most important and widely used active ingredients accounting for up to 73% of total herbicide active ingredients used across the seven countries, viz. Australia, China, India, Indonesia, Philippines, Thailand, and Vietnam and up to 38% of the total area sprayed with herbicides. Also, the expenditure of using alternate methods for glyphosate may increase the annual cost of weed control across the seven countries between \$22/ha and \$30/ha (Brookes, Barfoot, 2018). Annually, Asia accounts for the use of about 82 million kg (16%-18% of global use) of glyphosate as active ingredients associated with agricultural uses per year. Glyphosate is one of the most important and widely used active ingredients accounting for between 13% and 73% of the total herbicide active ingredient use across Asia and stands between 7% and 38% of the total area sprayed with herbicides (Brookes, 2020). India and China, two agriculturally important countries use 20.1 and 14.2 million kg glyphosate as active ingredients in various herbicide formulations. However, resistance to glyphosate is evolving at a steady pace which results in low efficacy and higher weed management costs (Heap, Duke, 2018). There are more than 48 glyphosate-resistant weed species in the world (Heap, 2021). Hence, with new transgenics, the threat of poor efficacy of glyphosate has become a major cause of concern.

3.3 Weed shift

With the technological shift from subsistence to intensive and commercial cultivation and from conventional to conservation ecologies, a distinct weed shift towards difficult to control weeds has been noticed. For example, before the Green Revolution in India, *Carthamus oxycantha* L. was one of the major weeds of wheat, but with the expansion of irrigation facilities and introduction of semi-dwarf norin wheat, *Phalaris minor* Retz. and *Avena ludoviciana* L. have

become noxious weeds (Yadav, Malik, 2005). A paradigm shift in crop establishment with the popularization of resource conservation technologies, eg. zero tillage (ZT) in India has also resulted in a shift towards perennial grassy weeds *Agropyron repens* (L.) Beauv. And *Cirsium arvense* (L.) Scop. over broad leaved weeds such as *Convolvulus arvensis* L. and *Rumex dentatus* L. (Chhokar et al., 2007; Catizone et al., 1990). Climate change owing to increased temperatures and higher CO₂ concentrations may cause a potential shift of weeds with less phenotypic plasticity and allow some other weeds to replace native and expand in newer areas (Peters et al., 2014). These weed shifts in intensive systems have compelled the continuous use of high-efficacy and recently introduced low-dose herbicides. With a lack of choice in the existing herbicides, the dependence on a few herbicides has become troublesome.

3.4 Environment concerns and herbicide banning

Chemical weed management using herbicides is an inexpensive and effective means of weed control, but the continuous use of herbicides for long might contaminate soil, water, and air (Zang, 2018). Contamination of water resources through adsorption, absorption and precipitation, degradation into a harmful substance or transportation through leaching, volatilization and runoff, especially through pre-emergence or pre-planting is a grave concern. When herbicides reach sites not accessible for roots, they contaminate groundwater (Mendes et al., 2021). The steep increase in the use of herbicides, especially glyphosate in South Asia under intensive systems is a cause of concern. Resistance against glyphosate in several weeds has been reported across more than 35 countries, including South Asia, in almost 35 major crops (Heap, Duke, 2018). The persistence of glyphosate may exceed up to years, therefore, a huge area of global croplands is susceptible to high environmental pollution and eco-system hazard (Richmond, 2018). Glyphosate belongs to a 2A category as probably carcinogenic to humans (International Agency for Research on Cancer, 2015). In India, the ban on manufacturing and sale of 27 pesticides, including important herbicides like atrazine, 2,4-D, pendimethalin, sulfosulfuron, oxyfluorfen, butachlor, etc., is in process. Anticipating the negative environmental footprints with glyphosate use, the state of Punjab, Kerala, Telangana and Andhra Pradesh of India have already banned the use of glyphosate (Mukherjee, 2020). Glyphosate is also totally banned in Sri Lanka. Some other herbicides viz. hexazinone and diuron, have been reported as microcontaminants of soil and water resources located near the application sites (Mendes et al., 2019).

3.5 Poor herbicide efficiency

Major challenges in herbicide use in developing nations are the mixing of spurious material with poor raw

material and low quality of solvents, inappropriate dose, and method of application (Bayoumi, 2021). The under or over-dose for severe weed infestation may also lead to poor weed management and phytotoxicity in some cases. With the increasing use of specific herbicides against specific weeds, their efficacy against other weeds remains at stake. Thus, using appropriate herbicides and their combinations for effective weed control is needed. The evolution of herbicide resistance and the differential response of weeds and crops to the herbicide demand new herbicides, which are usually expensive. Managing herbicide use for effective and sustainable weed control includes factors like herbicide selection, their doses, time, and method of application.

3.6 Scarce information on herbicide use for farmers

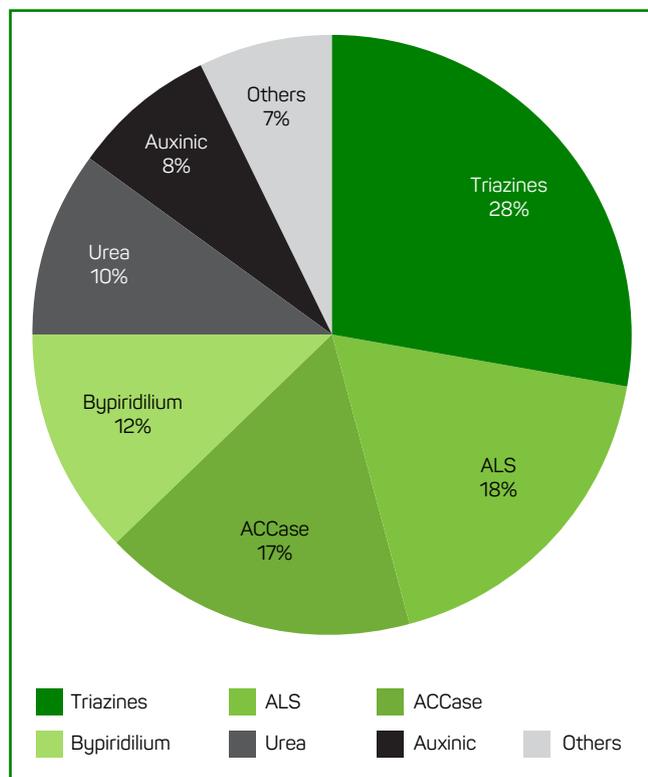
The knowledge of the majority of the management systems is still at the nascent stage and is incomplete. Various programs must be carried out under human resource development schemes to strengthen the extension services to farmers. Besides the economic and environmental risks, the farmers in South Asian countries do not even follow the personal protective equipment while spraying herbicides. Adhikari et al. (2020) from Nepal reported that various socio-economic factors, including farm size, education level, and migration governs the use of the herbicide. Individual herbicides offer immediate advantages, thus herbicide use is advised in combination with agricultural measures to increase agricultural production costs. A poor understanding of the possible evolution of herbicide resistance by continuous and extensive use of herbicides makes farmers unaware of the threat. Alternative herbicides with novel MOA are very few and their information is very scarce amongst farmers. Some natural phytotoxins based on citronella oil, d-limonene, pine oil, pelargonic acid, etc., are known to provide new and potential target sites. These natural products must be popularized among farmers, but the high cost incurred makes their use a challenge.

3.7 Herbicide resistance

When a weed biotype survives the dose of a herbicide to which it used to be controlled earlier is said to be called a herbicide-resistant (HR) weed biotype. Out of the total weed population, if 15% or more weeds develop resistance, alternate weed management options are advised. Over time, the proportion of these resistant weed biotypes increases with continuous selection, resulting in the building of a genetically resistant weed population (Vencill et al., 2012).

2,4-D was the first herbicide against which resistance was reported in *Daucus carota* L. in Canada in 1957 (Stachler et al., 2000). Then in 1968, resistance was reported in the USA against atrazine and simazine (triazine group) in *Senecio vulgaris* L. (Ryan, 1970). However, with time, herbicide resistance has been reported against almost all

the major herbicide groups in the developing nations also, however, most resistance cases have been reported against triazines (Figure 1). Herbicide-resistance cases in rice weed species have been reported from the way back in 1989 against 2,4-D from Malaysia. Later, herbicide resistance against propanil, quizalofop-p-ethyl, fenoxaprop-p-ethyl and bensulfuron-methyl from Malaysia, Thailand, the Philippines and Indonesia have been also reported (Kumar et al., 2017).



Note: ACCase: Acetyl CoAcarboxylase inhibitors; ALS: Acetolactase synthase inhibitors.

Figure 1 - Distribution of herbicide-resistant cases in developing nations based on the mode of action (Source: Heap, 2021).

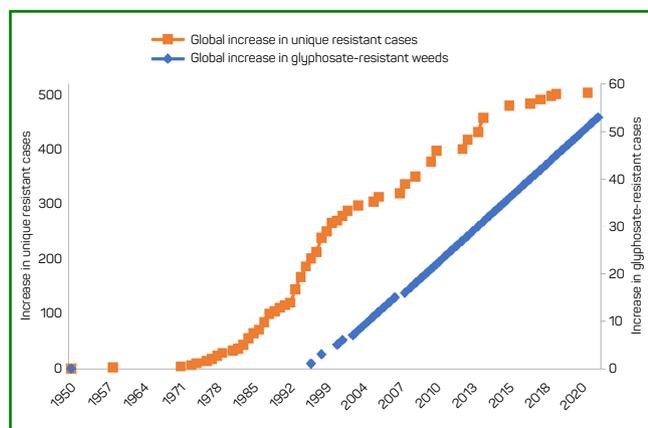


Figure 2 - The increase in the number of unique cases and glyphosate-resistant cases over time (Source: Heap, 2021)

Any weed species that become resistant to a specific herbicide is called a unique case. When the same weed species become resistant to another herbicide, it becomes a separate unique case. A total of 263 weed species; 152 belonging to dicotyledonous and 111 to monocotyledonous have been reported resistant as the total 502 unique cases. Heap (2021) reports that resistance has been involved in more than 160 different herbicides in 95 crops in 71 different countries. The resistance has been reported for more than 20 MOA out of the total 31 known herbicide sites of action. The chronological increase in the total unique resistant cases and glyphosate-resistant cases alone has been reported after 1980 (Figure 2).

Although the majority of cases of developing herbicide resistance have been reported in the developed world due to intensive herbicide use and popularization of HR crops, several important weeds have evolved resistance in developing countries, also (Rao et al., 2017). The developed countries account for approximately 70% of the global agrochemical market and glyphosate alone accounts for nearly 11% of the total market; however, in developing countries, paraquat is the most used herbicide (Choudhary et al., 2014). Also, in developing countries, manual weeding is still the most commonly used method of weed control. But now, almost 22% of the HR cases have been reported from developing nations only. Herbicides against which resistance has been reported in different weeds grown in various crops from South Asian countries have been listed in Table 1.

Table 1 shows that resistance has been developed primarily in weeds occurring in wheat and rice in South Asia. Herbicide resistance is a major problem for developing countries due to their higher reliance on food crops and escalating costs of cultivation, thus it might have implications on the profitability of major crops. Agriculture is the primary source of livelihood in these areas and higher food demands for burgeoning populations remain a challenge. Also, herbicide resistance has been reported to be the highest in cereal crops across South Asian countries (Table 2). Figure 3 also highlights that the maximum resistance cases in weeds have been reported in cereals.

4. Sustainable weed management in South Asia

4.1 Improving herbicide efficiency

Higher efficiency of weed control using chemical management can be achieved through the adoption of herbicide sequence, herbicide rotation, development of novel herbicides and herbicide mixtures, use of synergists, new formulations, or new adjuvants; and use of appropriate herbicide rates (Calore et al., 2015). Besides improving efficiency, they can also delay the development of resistance (Gressel, Segel, 1990). Spraying the prescribed doses of herbicides under appropriate environmental conditions, viz. wind velocity, luminosity,

| Table 1. Herbicide resistance in weeds, mode of action of herbicides, and alternative suggested effective herbicides. | | | | |
|---|---|-----------|---|--|
| Herbicide | Mode of action | Country | Alternative herbicides | Reference |
| <i>Phalaris minor</i> in wheat | | | | |
| Isoproturon | PSII inhibitors - Serine 264 Binders (HRAC 5) | India | Clodinafop-propargyl, sulfosulfuron, fenoxaprop-ethyl, tralkoxydim, pinoxaden, and diclofop-methyl | Malik and Singh, 1995; Das, 2008 |
| Isoproturon resistance biotype showing cross-resistance to diclofop-methyl | PSII inhibitors - Serine 264 Binders (HRAC 5) and Inhibition of Acetyl CoA Carboxylase - HRAC Group 1 | India | Clodinafop-propargyl, sulfosulfuron, fenoxaprop-ethyl, tralkoxydim | Yaduraju and Ahuja, 1995 |
| Cross-resistance to clodinafop-propargyl | Inhibition of Acetyl CoA Carboxylase-HRAC Group 1 | India | Sulfosulfuron, pinoxaden fenoxaprop-ethyl | Das et al. 2014, Bhullar et al. 2014 |
| Sulfosulfuron | Inhibition of Acetolactate Synthase-HRAC Group 2 | India | Pinoxaden | Chhokar and Sharma 2008 |
| Clodinafop-propargyl, fenoxaprop-p-ethyl resistant biotype showing cross-resistance to pinoxaden | Inhibition of Acetyl CoA Carboxylase - HRAC Group 1 | India | Sulfosulfuron and Metribuzin | Kaur et al. 2015 |
| Multiple resistance against isoproturon, sulfosulfuron, clodinafop propargyl, fenoxaprop ethyl, and pinoxaden | PSII inhibitors - Serine 264 Binders (HRAC 5) (isoproturon), Inhibition of Acetolactate Synthase-HRAC GROUP 2 (sulfosulfuron), Inhibition of Acetyl CoA Carboxylase-HRAC Group 1 (clodinafop propargyl, fenoxaprop ethyl and pinoxaden) | India | Metribuzin and terbutryn | Chhokar and Sharma 2008 |
| Fenoxaprop-ethyl | Inhibition of Acetyl CoA Carboxylase HRAC Group 1 | Pakistan | Use herbicides mixtures e.i. clodinafop-propargyl + metribuzin, pinoxaden + sulfosulfuron, and pinoxaden + metribuzin | Abbas et al. 2017 |
| <i>Rumex dentatus</i> in wheat | | | | |
| Metsulfuron-methyl | Inhibition of Acetolactate Synthase - HRAC group 2 | India | Carfentrazone, 2,4-D amine and metribuzin. | Chhokar et al. 2013; Chaudhary et al. 2021 |
| Florasulam, iodosulfuron-methyl-Na, mesosulfuron-methyl, and pyroxulam | Inhibition of Acetolactate Synthase-HRAC Group 2 | India | Carfentrazone, 2,4-D amine | Heap 2021 |
| <i>Cyperus difformis</i> L. in rice | | | | |
| Bispyribac-sodium | Inhibition of Acetolactate Synthase - HRAC Group 2 | India | florpyrauxifen-benzyl | Choudhary et al. 2021 |
| <i>Conyza sumatrensis</i> Retz. in tea | | | | |
| Paraquat | PS I Electron Diversion HRAC Group 22 | Sri Lanka | - | Heap 2021 |

*HRAC, Herbicide resistance action committee

relative humidity, and temperature, might delay resistance evolution (Norsworthy et al., 2012). Also, the standardized application technologies like appropriate nozzle type, speed of application, tank pressure, droplet size, use of surfactants, and spray volume are essential to maximize efficacy and avoid resistance selection by sub-doses (Busi et al., 2013).

Cross-resistance and multiple resistance would be delayed or relieved when herbicide sequence, rotation, and/or mixture are used concurrently. When weeds develop non-target site resistance, the synergist application, formulation changes, and the use of new adjuvants also aid in managing herbicide resistance by increasing the

| Table 2. Herbicide resistance in weeds under important crops in Asian countries (Peterson et al. 2018). | | | |
|---|------|-------|-------|
| Country | Rice | Wheat | Maize |
| Bangladesh | * | - | - |
| India | * | ** | * |
| Pakistan | * | ** | - |
| Sri Lanka | ** | - | - |
| Nepal | * | ** | - |

*resistance has been reported, but not significant; **resistance severe threat to crop production; -area under the crop is limited

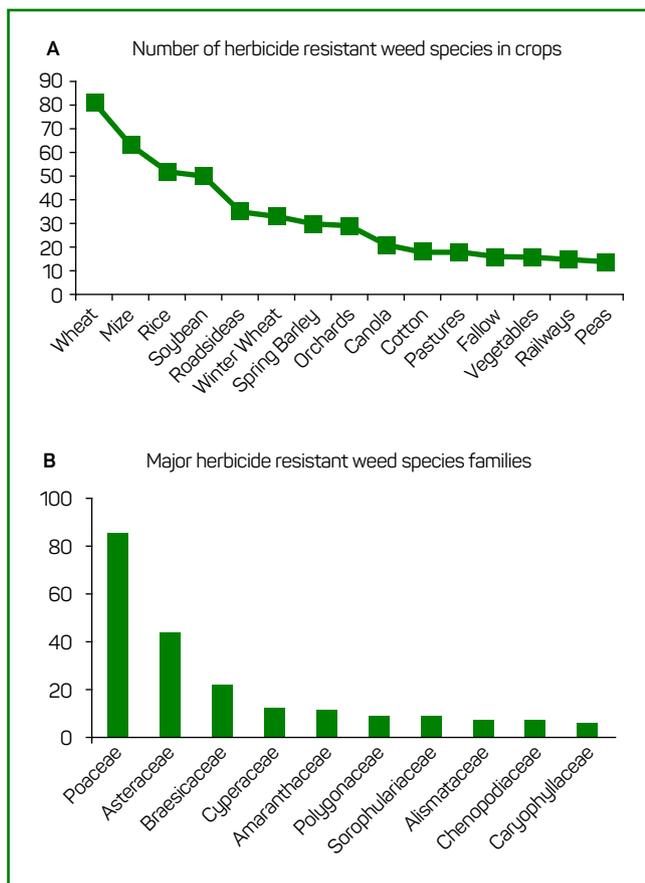


Figure 3 - The prevalence of herbicide-resistant weed species in various crops (A) and herbicide-resistant weeds species families (B). [Source: Heap, 2021]

concentration of herbicidal ingredients at the target sites. Lower or higher than the recommended dose of herbicides promotes the rapid evolution of polygenic resistance (Lagator et al., 2013; Yu et al., 2013).

4.2 Early detection of herbicide resistance

Herbicide resistance causes substantial yield losses, agro-ecosystem imbalance, and food safety issues (Atashgahi et al., 2018). The frequency of the herbicide use pattern, as the sole application or in mixtures, also governs the development of herbicide resistance, but herbicide rotation can only be followed up on the availability of alternative herbicides.

For the prevention of herbicide resistance in the areas where it has not been established, the selection pressure for resistant biotypes should be reduced. The appropriate herbicide dose, efficacy, and frequency of application should be chosen. The admixture of resistant weed seeds also introduces herbicide resistance in new areas, hence certified weed-free seeds and clean farm machinery and equipment also prevent the dispersal of resistant weed seeds.

Early-emerging weeds often survive post-emergence weed control practices due to their large size and stature at

the time of herbicide application. Thus, an early detection of herbicide resistance through various techniques *viz.* hydroponically grown weeds for rapid access to root and shoot growth behaviors, use of selected marker genes which help in identification of those genes which have conferred resistance to various herbicides, or models for better understanding of the management scenarios, and early prediction and risk assessment through long-term field trials studying weed population dynamics for better understanding and timely decision making could prevent or delay the development of herbicide resistance (Bagavathiannan et al., 2020). Physical management of HR weeds includes soil solarization, deep plowing, selection of clean crop seeds, and soil mulching. When combined, these physical management techniques can prevent over 95% of resistant weed seeds from entering the soil seed bank (Walsh et al., 2018).

4.3 Herbicide resistance stewardship

The popularization of the rice-wheat system and the continuity of the same system has paved a way for the incidence of isoproturon-resistant *P. minor* in wheat in India (Malik, Singh, 1995). If resistance is suspected and later confirmed, the herbicide being used should be immediately stopped. The resistant weed plants should be killed before seed setting and dispersal. Best management practices, *viz.* employing higher plant density, staggered planting time, and managing resistant weed populations should be focused on. Site-specific agronomic manipulations in tillage, residues use, and selection of suitable crop rotations can reduce or delay the evolution of herbicide resistance. Also, the inclusion of a short duration legume crop like mungbean (*Vigna radiata* (L.) R.Wilczek) in the Indo-Gangetic Plains potentially reduces weed pressure by maintaining soil mulch (Kumar et al., 2013). Thus, integrating all management factors can help in dealing with herbicide resistance (Figure 4).

4.4 Switching to newer herbicides

Using alternate herbicides as an integrated weed management (IWM) strategy can delay and sometimes prevent the problem of herbicide resistance development. In India, IWM has given some practical solutions for herbicide resistance in *P. minor* in wheat. The resistant plants are able to metabolize the herbicide with increased activity of monooxygenase enzymes and poor degradation of isoproturon due to the mixed function of oxidase inhibitors, 1-aminobenzotriazole (ABT) and piperonyl butoxide (PBO) (Singh et al., 1998). Herbicides with alternative MOA, *viz.* tralkoxydim and diclofop-methyl, have been reported to control isoproturon-resistant *P. minor* (Walia et al., 1997). But, with time, isoproturon-resistant weed biotypes exhibit cross-resistance to clodinafop-propargyl and sulfonyleureas also. However, herbicides like fenoxaprop-

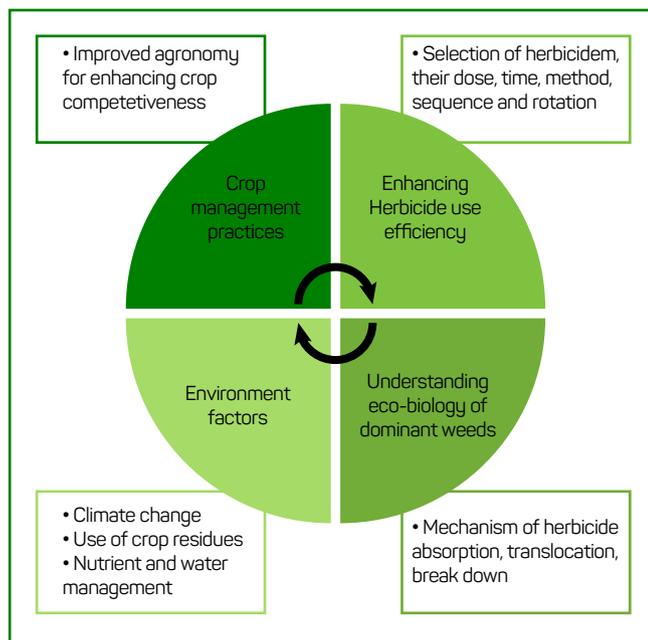


Figure 4 - Herbicide resistance stewardship with the integration of crop-herbicide-weed factors

p-ethyl, sethoxydim, tralkoxydim, and the dinitroanilines, trifluralin, and pendimethalin, remains effective (Chhokar, Malik, 2002). Herbicide rotation with alternate MOA can significantly delay the development of resistance in weeds. In place of a single herbicide, mixtures such as metsulfuron + iodosulfuron and fenoxaprop + metribuzin have also been introduced to control resistant *P. minor*. In major South Asian countries, glyphosate-tolerant crops are less popular and a variety of herbicides and their rotations are in use without the development of resistance.

4.5 Herbicide-tolerant crop management

Weed management is more crucial in herbicide-tolerant (HT) crops, as the presence of weeds may encourage gene flow by pollen or seed dispersal (Bain et al., 2017). To manage HT crops, the minimum use of herbicides should be used to achieve a yield level higher than conventional crops. For these crops, instead of using higher doses, a tank mix application with other herbicides is advised (Schütte et al., 2017). In India, the recently released HT rice cultivars Pusa 1979 and Pusa 1985 have been developed using marker-assisted backcross breeding which is tolerant to the imidazolinone group of herbicides through introgression of mutated acetohydroxy acid synthase (AHAS) alleles (Grover et al., 2020). Herbicide tolerance has been conferred against imidazolinones in several other crops, popularly known as Clearfield crops.

4.6 Integrated herbicide resistance management

Resistance to herbicides in weeds is an outcome of natural selection in the presence of selection pressure exerted by

herbicides, which are in continuous use without proper levels of risk assessment. Also, herbicides alone cannot create resistant weeds. Thus, an integrated herbicide resistance management system is desired to better fit the diverse local ecological regions of South Asia (Shekhawat et al., 2017). Developing more effective integrated management systems against herbicide resistance, understanding the biology and ecology of crop-weed interactions and elucidating herbicide resistance mechanisms (especially for the non-target-site-based resistance) remains necessary. More focus should be given to preventive measures and delay the development of new resistance management strategies under non-chemical approaches. Thus, concerted efforts from scientists, farmers, manufacturers, and policymakers can address this issue.

Cases of resistant weeds in rice production in India and across South Asia are less common, possibly because of the prevalence of hand-weeding in these areas compared with the developed world. But, hand-weeding as a weed management strategy is losing importance due to higher wages and the availability of herbicides, and thus, resistance in weeds is emerging. The current estimates are that 70% of the rice production areas in India is treated with herbicides for weed control (Choudhary et al., 2014). But, fortunately, the majority of the herbicides being used in rice belong to the very long-chain fatty acid (VLCFA) inhibitor and ALS inhibitor groups. VLCFA inhibitors are generally applied as pre or early post-emergence to control grasses and have a lower tendency to develop resistance.

The post-emergence applications of ALS inhibitors to manage broadleaf weeds in rice across Asia exhibit more resistance issues. Resistance in grass weeds, especially *P. minor* to ACCase and ALS herbicides, is one of the major challenges for wheat farmers across India, Pakistan, Bangladesh, and Nepal. Multiple herbicide-resistance in *P. minor* impacts nearly 4 M ha area in the top 10 wheat-producing states in India. Non-chemical weed management practices, including stale seedbed, early planting, higher wheat seeding rates, herbicide rotations, and sequential herbicide applications, are currently being recommended for the management of problem species, such as *P. minor*.

4.7 Improved agronomy for enhancing crop-competitiveness

Agronomic manipulations through the selection of crops, crop rotations and intercropping, crop establishment techniques, spatial arrangement, and other crop management factors including nutrient, water, mulching (Dass et al., 2016; Yang et al. 2018), the optimum time and density of sowing (Deng et al., 2018), use of allelopathy (Li et al., 2018), etc., improve the weed control efficiency.

4.7.1 Crop establishment and sowing

The staggered sowing time which can modify the crop-weed competition to favor crop growth can reduce weed infestations. For example, the shifting of wheat sowing 15

days later during the first fortnight of November can reduce infestation of noxious weeds, like *P. minor*, in India and due to higher temperature at the terminal stage, the seed formation in *P. minor* can be avoided.

The timing and method of tillage strongly influences the dominance of weed flora. Timely sown zero-tilled wheat can compete with *P. minor* infestation, with or without crop residue retention (Chhokar et al., 2007; Kumar et al., 2013). Early wheat sowing under ZT with anchored residues resulted in a significant reduction in the emergence of *P. minor* in wheat (Kumar et al., 2013). Besides saving labor and energy, ZT wheat also reduces the seed bank of *P. minor* and several other broadleaved weeds, viz. *Rumex dentatus*, *Melilotus indica*, and *Coronopus didymus* L. over conventional tillage (CT) (Shekhawat et al., 2021; Kumar et al., 2015). However, the proliferation of perennial weeds e.g. *Richardia scabra* L. and *Cynodon dactylon* (L.) Pers. under conservation agriculture (CA) in Pakistan have been reported by Farooq and Siddique (2015).

In India, under CA systems, in-situ management of paddy stubble has become possible using Turbo Happy Seeder as planter-cum-seeder. It is a tractor-operated machine developed by Punjab Agricultural University and in collaboration with Australian Centre for International Agricultural Research (ACIAR) and facilitates sowing of wheat with a residue load of up to 8 t/ha. A stale seedbed after maize or soybean promotes weed emergence, which can be easily killed with the application of non-selective herbicides, like paraquat, to reduce weed competition in succeeding wheat. This technique helps eliminate weed seed bank from deeper layers which also discourage weed seed germination from deeper layers. Crop residue retention with ZT sowing has been reported to reduce weed infestation in wheat by up to 40% under the rice-wheat system (Chhokar et al., 2009). But at the same time, many soil-active herbicides get adsorbed by crop residue and become less effective, therefore, post-emergence herbicides or biocontrol agents should be preferred. Under ZT, crop residues minimize the soil surface exposure to sunlight and offer physical hindrance, which inhibits annual weed species to activate a phytochrome-mediated germination process before emergence (Baghel et al., 2020). However, the rate of suppression depends upon the weed species of concern, crop species, the span of weed infestation during the crop duration, and the amount of biomass being added. On the contrary, under conventional systems, weed seeds' exposure to sunlight after tillage stimulates their germination and emergence. Stale seedbed, however, can be useful under both conventional and conservation systems. Under CT, a shallow plowing of weeds will further reduce the weed seed bank in the soil. While under CA, the emerged weeds can be killed using a non-selective herbicide. Thus, following stale seedbed as per the crop establishment method would help to reduce the weed seed bank in the soil.

4.7.2. Crop rotation and diversification

The understanding of the biological and ecological characteristics of weeds, the direct (or preventive) and indirect (or curative) weed management methods can be modulated through cultural practices like crop diversification (Sardana et al., 2017). They disturb and disrupt weed niches and delay the evolution of herbicide resistance (Liebman, Davis, 2000). In the trans-Indo-Gangetic Plains of India, despite confirmed herbicide resistance in *P. minor* biotypes in the rice-wheat system, only 14% of farmers are practicing diversification and the remaining 86% still follow rice-wheat monoculture (Chhokar et al., 2017). Crop rotations following winter maize, clover, alfa-alfa, and lucerne, or even sugarcane ratoon have been proven to reduce *P. minor* infestation in the fields (Singh et al., 1998). In Pakistan, fallow-barley, mungbean-barley, and cotton-barley crop sequences recorded better weed control under CT and bed-sowing (Naem et al., 2021). Growing green manure crops as an intercrop has been reported to reduce the density of broad-leaf weeds in rice (Singh et al., 2007).

4.7.3. Mulching: Living cover crop

A more diverse biological and physical environment at the surface of soils, through live mulches and cover crops, minimizes weed infestation. The living mulch offers more advantages than desiccated crop residues. Besides weed suppression, live mulches, especially legumes, provide various ecological benefits like reducing soil erosion, soil fertility enhancement, and altering pest populations (Hartwig, Ammon, 2002). The fast-growing and maturing live mulch as a smoother crop between main crops results in up to 90% of weed biomass reduction (Liebman, Staver, 2001). Reductions in weed infestations with sunhemp (*Crotalaria juncea* L.) as a living mulch in avocado (*Persea americana* Mill.) and weed dry weight by 34 to 51% with hairy vetch (*Vicia villosa* Roth) has been reported. Likewise, velvetbean (*Mucuna pruriens* L.) suppressed the radical growth of the local weeds Alegria (*Amaranthus hypochondriacus* L.) by 66% and barnyardgrass (*Echinochloa crusgalli* L.) by 27% (Mohammadi, 2010).

The selective suppression of weeds by the smoother crop is highly desirable. Thus, a low-growing live mulch would exclude light for weed seed germination.

The mulch area index and solid volume fraction are important mulch properties that govern the soil microclimate, soil moisture evaporation, and temperature. The residue with a higher C: N ratio does not decompose fast and is thus, desirable for longer weed control. The crop residues reduce weed seed germination by reducing the minimum temperature required for weed seed germination (Choudhary et al., 2020). However, not all weed management strategies are equally compatible with cover crops. Cover crops should be established before weed emergence, which will reduce the use of herbicides, especially pre-emergence herbicides. Also, the peak growth

of mulch should not coincide with the peak growth of the main crop and additional nutrients and other inputs should be supplied to the crop to avoid any competition. But, some studies conducted in Pakistan revealed that soil moisture retention due to residues also stimulates germination (Shahzad et al., 2016). A soil or dust mulch created by shallow plowing also makes weeds less competitive to crops.

4.7.4. Brown manure

The productivity and sustainability of most of the CA-based systems in Indo-Gangetic Plains, including northern and eastern India, northeast of Pakistan, and the whole of Bangladesh, can be enhanced with the introduction of brown manure. Brown manuring is practiced under no-till systems as an alternative to green manuring where a non-selective herbicide is used to desiccate the crop along with the weeds at the flowering stage. Residue management, the evolution of herbicide resistance, and declining soil fertility can be improved through sesbania brown manuring (Ali et al., 2012). Sesbania is a fast-growing and high biomass-producing legume crop, which competes with weeds for space. The early elimination of weeds through brown manure and the addition of nutrients after decomposition are the dual benefits of this technology (Shekhawat et al., 2020). In Pakistan, the density of broad-leaved weeds, narrow-leaved weeds, and sedges have been reported to reduce weeds by 56%, 41%, and 50%, respectively, over sole rice crops under brown manure (Nawaz et al., 2017).

4.7.5. Nutrient application

The nutrient application must favor crops in place of weeds, thus site-specific nutrient management helps in providing nutrients as per the crop demand and when the crop stage can take maximum advantage of the fertilizer application. Fertilizer application, especially nitrogen (N) fertilizers may be used to favor crop plants against weeds. N application improves crop growth and enhances residue degradation, and thus, can be used as cultural management of weeds. Several reports highlighted the impact of N application on grassy weed management in wheat, and higher N rates increased the competitive ability of cereals (including wheat) to suppress weeds (Rishi et al., 2020; Das, Yaduraju, 2007; Singh et al., 2015). Manipulating N dose, its scheduling, and method of application can be a possible management option for weed control. The impact of higher N rates to suppress weeds in wheat has been reported from India (Das, Yaduraju, 2011). The higher dose of N could benefit wheat crops by enhancing its competitiveness and reducing *P. minor* interference through reducing tillers and dry weight.

4.7.6. Allelopathy

Many crops and weed species have been observed to have allelopathic properties. Over 240 weed species have

been reported to be allelopathic to other plants of the same species or other crop and weed species (Colquhoun, 2006). The use of allelopathy to suppress weeds either before the crop season, utilizing the allelopathic effect in the standing crop, or by extracting the allelopathic substance produced from the plant and then applying it to the weeds. The allelopathy from crop residue incorporation of sorghum residue before planting wheat, and rapeseed residue before potato, can suppress weeds (Cheema, Khaliq, 2000). In Pakistan, the lowest weed infestation was recorded in a crop sequence containing sorghum due to its strong allelopathic ability to suppress weeds (Jabran, 2017). In a similar study, buckwheat was found to alter the growth of *Amaranthus retroflexus* L. with its root exudation which ultimately suppresses the weed growth (Latif et al., 2017).

However, the extent of weed control through allelopathy depends upon the concentration of the allelochemicals (Nawaz et al., 2018). Using allelopathy as a weed management approach has been widely studied in crops such as sorghum, tobacco, eucalyptus, rapeseed, sesame, rice, and sunflower (Jabran, 2017). Farooq et al. (2017) in Pakistan recorded a significant reduction in weed seed germination using sorghum water extract. The use of water extracts of brassica, mulberry, and sorghum in maize reduced the density and dry biomass of *Cyperus rotundus* L. and *Trianthema portulacastrum* L. than the control (Ihsan et al., 2015). Mahmood et al. (2013) also reported a decrease in density and dry biomass of weeds in maize due to foliage application of multiple allelopathic extracts. Naeem et al. (2016) found a reduction in the density of *T. portulacastrum* and *C. rotundus* due to the combined application of sunflower and sorghum water extracts in maize. In another study, Khaliq et al. (2010) reported weed suppression in maize due to the use of allelopathic crop mulches.

5. Integrated weed management (IWM)

The use of pesticides in agriculture is increasing rapidly in developing countries, especially in South Asia (Brown et al., 2021). India is the 12th largest pesticide manufacturer in the world. It is already producing 90,000 t pesticides/annum. Thus, sole dependence on herbicides alone for weed management is neither sustainable nor ecologically desirable.

Also, no single method is full-proof, adoption of an appropriate IWM strategy not only keeps the weed populations below economic threshold levels but also delays the resistance development in weeds. IWM is the ecologically sound and holistic management principles-based plan to minimize weed populations. It focuses on both prevention and curative tactics to combat tenacious weed problems of agro-ecologies. IWM highlights redesigning, reshaping, and restructuring the natural ecologies in response to weed shifts and weed dynamics in the light of climate change and agronomical alterations.

The use of diverse non-chemical, cultural, and preventive tactics of weed management in integration also reduces the selection pressure for the development of herbicide resistance in weeds (Figure 5).

The judicious combination of all these tactics can potentially combat the weed menace in the long run. A successful and acceptable IWM strategy can be made by choosing effective tactics like staggered sowing, plowing, higher seed rates, and competitive cultivars (Shaw et al., 2012; Islam et al., 2018). In Bangladesh effective weed management using hand weeding along with herbicides has been also reported for wheat by Wara et al. (2020). Despite several challenges in following IWM, viz. slow action, cumbersome, variable response, less predictive, and higher cost, it can offer a long-term sustainable solution to the weed menace. In India, the success of the integration of various weed control methods for *P. minor* in wheat in India has been reported (Bhullar et al., 2017) (Figure 6). The combination of all the tactics can lead to a decline in *P. minor* populations by up to 90%.

6. Future research thrust

The challenges of intensive cultivation, possible weed shifts under climate change, and the shrinking genetic base of crop cultivars continue to put pressure on evolving effective and sustainable weed management protocols. Although, there is no practical, economic, and feasible alternative to herbicides in large areas, the development of new herbicide molecules with a unique mode of action remains desirable. Various other emerging technologies can

be accessed and the focus should be given to some future thrust areas. While developing newer herbicides, the use of some old herbicides can also be prolonged by utilizing negative cross-resistance where weeds are sensitive to some herbicides within the resistant class. The structured surveys and effective screening and diagnosis of HR weeds in the affected areas would pave the way for the adoption of newer herbicides with possibly different MOA and novel target sites. Some refinement in farm mechanization, including seeding, plowing, and herbicide applicators for the blanket and inter-row mechanical weed management remains necessary. Also, improving farm mechanization and automation in terms of robotics, drones, hyper-spectral imaging, crop models, and decision support systems can be explored for timely weed management under agricultural production systems.

We must rely on novel transformational weed management technologies and innovations (e.g. genetic engineering) and a thorough understanding of weed biology and ecology, weed seed bank, and population dynamics can revolutionize the weed vis-à-vis resistance management strategies and technologies. Gaining acceptance for alterations in agronomic practices by the farmers' community needs patience and perseverance. To change the existing beliefs, the modules for dissemination of proven technology and site-specific recommendations under capacity-building programs should be initiated.

7. Conclusions

In most agricultural systems, weed competition is the major factor limiting the farm income and profitability in both developed nations and developing nations. Weed management in South Asian countries is far more challenging as either the expenditure on weed control is very

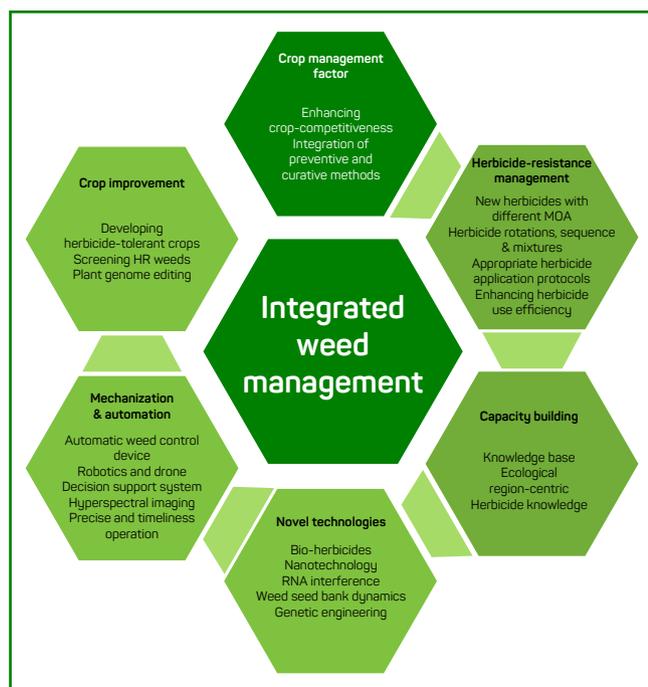


Figure 5 - The interrelation of various components for integrated weed management

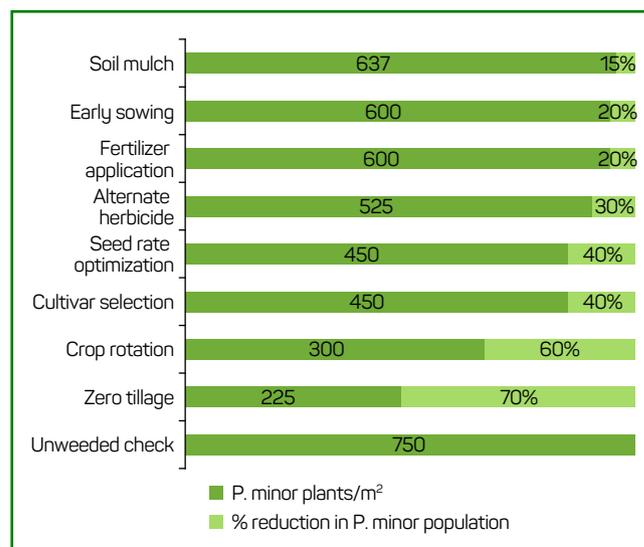


Figure 6 - The potential of various cultural management practices in reducing *P. minor* population in wheat

high or the losses due to weed management are huge. This review has highlighted the implications of intensive and extensive herbicide use, the issues of emerging herbicide resistance, and the importance of IWM for sustainable weed management in developing South Asian countries. Chemical weed management is simple, reliable, and cost-effective, yet the environmental concerns are huge. Keeping chemical weed management as a sole option and relying on similar herbicides for a long time will lead to evolution in due course.

Resistance is inevitable and weed populations often adapt and evolve in response to new selective pressures. Like crop plants, understanding weed succession and their stabilization in fields is apt. Developing herbicides with a new mechanism of action and a synchronized strategy to manage weeds without letting herbicide resistance evolution among weeds is needed. Also, alternative methods of weed

management remain always important. Sound knowledge of both agronomy and weed science, including biology, ecology, physiology, genetics, epigenetics, population dynamics, mechanisms, and dispersal of resistant weeds might address weed menace in long run. Similarly, effective crop rotations, alternate crop establishment methods, fallowing, higher crop competitiveness, and preventive and mechanical weed management, along clean cultivation practices, remain desirable. The advances in deep learning using computing power, robotics, and life sciences integrated with existing methods open multiple paths for sustainable weed management through precise monitoring and management of pests.

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