



REVIEW ARTICLE

A review of weeds management approaches in potato in India

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Abstract

Potato (*Solanum tuberosum* L.) is a globally vital staple food. Weeds infestation remains a major challenge to potato cultivation worldwide. They compete with crop plants for nutrients, sunlight, space and water, ultimately reducing both yield quantity, quality and enhancing insects and diseases infestation. Effective weeds control through different practices is crucial for maximising potato production. Once weeds have established themselves in a field, it becomes difficult to control and eradicate them. Prevention is a key component of integrated weed management (IWM). In developing countries, hand and manual weeding and herbicide use are the most common methods for weeds control. However, the intensive use of herbicides has been accompanied by high production costs, weeds resistance, environmental pollution (especially surface water contamination) and adverse effects on non-target organisms. Consequently, reliance on herbicides alone is no longer considered sustainable. Therefore, focus is now on new methods of weeds control, such as cultural, biological, mechanical and biotechnological approaches that can be used in conjunction with chemical weeds control. Biotechnology is closely related with chemical weeds management because it helps in development of herbicide tolerant crops and makes herbicides use more sustainable and cost-effective. These weeds control methods can be combined as IWM to mitigate the negative environmental impacts of herbicides. Recognising the critical role of weeds management, this review aims to highlight emerging weed management strategies for potato cultivation.

Keywords: artificial intelligence; biotechnological tools; control methods; integrated weed management; *Solanum tuberosum*; weeds flora

Introduction

The potato (*Solanum tuberosum* L.) ranks as the fourth most important food crop in terms of production after rice, wheat and maize. It plays a crucial role in global food security due to its wide adaptability and high nutritional value (1). Originally native to the high elevations of the Andes in South America, it was introduced to Europe by Spanish conquerors in the late 16th century. By the early 17th century, it is believed to have arrived in India via Portuguese or British traders (2). Globally, total potato production is 376 million metric tonnes from 18.1 million hectares (ha), with an average yield of about 21 t/ha. Over the past six decades, global potato production has increased substantially, with Asia experiencing a six-fold growth, while Africa and Latin America have recorded comparatively smaller increases (3). While, Europe has experienced a drop of more than 50 % over that time, some north-western European nations have maintained or expanded their potato production over the past 10 years (4). The rise in global demand for frozen processed potatoes is the primary factor driving the rapid expansion in Asian countries, Latin America and the Middle East, as well as both inside and outside Europe (5).

Weeds play a significant role in limiting potato production through competition with the crop and by hosting other pests, resulting in a reduction in tuber yield and quality. Yield losses due

to weeds can range from 10–80 %, with severe effect on tuber production and quality, leading to reductions ranging from 33–86 % (6). Weeds compete with potatoes for nutrients, water and light. Effective weeds management is essential early in the potato growth cycle to maximise tuber yield and quality (7). Potato growers typically control weeds with herbicides applied after soil is “earthed up”, mounded around the plants before or after emergence to shield roots and tubers from sunlight, preventing greening and suppressing late-emerging weeds (6). In fact, well-timed manual weeds management may not always be realistic due to labour shortages, high wage rates and adverse weather conditions (7).

Challenges in weeds management

The wide range of weeds species, along with varying agronomic and climate conditions, poses challenges for weed management, as no single approach fits all cropping systems. Integrated weed management (IWM) is a multifaceted strategy for controlling weeds (8). This approach combines cultural, mechanical, biological, genetic and chemical techniques to effectively and economically manage weeds, minimising their effect on crops while maintaining satisfactory yields (8). The IWM strategies include choosing a crop variety that is adapted to a specific area, has an early growth habit and shows biotic and abiotic stress resistance. It also consists of effective crop rotation, tillage

practices, cover crops and some alternative weeds control techniques such as flaming, steaming, infrared radiation or sand blasting.

Chemical weeds management is one of the most effective approaches to minimise mechanical plant damage, prevent the transmission of mechanically transmitted viruses and stop early weeds development (7). Furthermore, the ease of use, low cost and efficiency of herbicides have made them more popular; however, if used without adherence to labels, they can waste resources and cause pollution (9). Drones and unmanned aerial vehicles (UAVs) under artificial intelligence (AI), which includes remote sensing and farm management, have proven to be potent, accurate, economical and sustainable. They help in locating weeds patches, reducing selection pressure on herbicide-resistant weeds and reducing herbicide diffusion in the surrounding environment (10). Although gene-editing technologies have the potential to manage weeds in farmlands through direct genetic control approaches, more research is still required to improve the viability and cost-effectiveness of biotechnological weeds management techniques (11). A suitable plan for managing weeds must be created to lessen their detrimental effects on yield and increase potato productivity. Several challenges are present while managing weeds in potato.

Herbicide resistance

The widespread emergence of herbicide-resistant weeds populations in various regions is largely due to the intensive and repeated use of herbicides with the same site of action (12). Seven herbicide-resistant weeds species have been identified in potato crops worldwide. These include *Chenopodium album* L., *Amaranthus retroflexus* L., *Amaranthus palmeri* S.Watson, *Atriplex patula* L., *Avena fatua* L., *Phalaris brachystachys* Link and *Phalaris paradoxa* L.

Production in arid areas and climate change

Reductions in precipitation in arid regions may reduce crop resilience while enabling weeds, with their adaptive defense mechanisms, to thrive longer than usual (13). Climate change can profoundly affect weeds management strategies. Weeds species can sometimes rapidly evolve to better suit changing weather conditions. Herbicides may need to be reformulated to withstand higher temperatures or adjusted in application methods to accommodate altered rainfall patterns.

Organic farming

Weeds management poses a significant challenge for organic farmers and is often considered a major barrier to transitioning to organic farming. In organic cropping systems, effective weed control strategies are limited due to the prohibition of herbicide use (14).

Integrated pest management (IPM)

Understanding the relationship between weeds, insects and diseases is crucial for developing effective IPM programs. A key challenge is identifying IPM strategies that effectively and harmoniously address both weeds and insects interaction.

Integrated weeds management (IWM)

It offers promise by reducing the weed seed bank and providing economic and environmental benefits through the integration of chemical, mechanical and biological control methods (15). Novelty

in IWM is crucial as agricultural systems face increasing complexity due to climate change, making weeds management more challenging (13).

Site specific weeds managements

Applying herbicides uniformly across weed populations that are unevenly distributed can result in inefficient weeds management. Adopting site-specific weeds management approaches can lead to more effective herbicide use, offering both ecological and economic benefits (16).

Technology dissemination

Advancements in weeds management technologies have not been adopted by farmers as quickly as improvements in high-yielding varieties, fertilisers and insecticides (17).

Weeds flora in India

Weeds vary in prevalence and severity across different agro-climatic regions in potato-based cropping systems (1). Species commonly found in potato fields of the plains such as Punjab, Haryana, Delhi, Uttar Pradesh, Bihar and West Bengal, include *Amaranthus viridis* L., *Anagallis arvensis* L., *Cyperus rotundus* L., *Cynodon dactylon* L. Pers., *C. album*, *Melilotus* spp., *Poa annua* L., *Phalaris minor* Retz., *Sonchus oleraceus* L., *Trianthema monogyna* L. and *Vicia sativa* L. The predominant weeds species associated with potato crop production in the hills, such as Himachal Pradesh, Jammu and Kashmir, Assam, Sikkim, Meghalaya, Karnataka and the Nilgiris hills of Tamil Nadu include *A. viridis*, *C. album*, *Chenopodium murale* L., *Melilotus indica* L., *Setaria glauca* (L.) P.Beauv and *Spergula arvensis* L. (18). In Assam (India), 33 weeds species from different families have been reported, with *Axonopus compressus* (Sw.) P.Beauv and *C. dactylon* being the most prevalent (1). In the Nilgiris hills, *Coronopus didymus* (L.) Sm., *Polygonum nepalense* Meisn. and *S. arvensis* were the predominant weeds (19). Table 1 presents major weeds found in various agro-ecological regions in plains and hills.

In a survey of weeds flora in north-eastern Haryana, India during 2004–05, a total of 23 weeds species were found in potato fields. The dominant species included *A. arvensis*, *C. album*, *Medicago denticulate* L., *M. indica*, *Polypogon monspeliensis* L. and *P. minor* (20). In central Uttar Pradesh, the key weeds that infested potato fields included *A. arvensis*, *C. album*, *C. rotundus*, *M. indica* and *V. sativa*. A total of 42 weeds species have been identified in potato fields of Meghalaya, with a dicotyledonous to monocotyledonous ratio of 2.4:1 (21). The most prevalent broad-leaved weeds in potato fields of the northeast region of India, specifically in Shillong, included *Hydrocotyle javanica* Thunb., *Oxalis griffithii* Edgew. & Hook.f., *Oxalis corniculata* L., *Polygonum alatum* Buch.-Ham. ex D.Don, *Plantago major* L. and *Solanum khasianum* C.B.Clarke. The dominant narrow-leaved weeds included *Arundinella khasiana* Hoof.f., *Arthraxon* sp., *Brachiaria reptans* (L.) C.A.Gardner & C.E.Hubb., *Cyperus cyperoides* (L.) Kuntze and *Paspalum orbiculare* G.Forst (22).

Global variation in weeds flora

In Indonesia, grass weeds (*C. dactylon*, *Eleusine indica* (L.) Gaertn.), sedge weeds (*C. rotundus*) and broadleaf weeds (*Oxalis latifolia* Kunth, *Portulaca oleracea* L., *Celosia argentea* L., *Drymaria villosa* Cham. & Schltdl., *Ageratum conyzoides* L. and *Hydrocotyle leucocephala* Cham. & Schltdl.) were reported (23). The dominant

Table 1. Most important weeds that affect potato crop in hilly and plain areas

Weed diversity in the plains	
<i>Amaranthus viridis</i> L.	<i>Cyperus rotundus</i> L.
<i>Avena fatua</i> L.	<i>Melilotus indica</i> L., All
<i>Asphodelus tenuifolius</i> Cavan	<i>Melilotus alba</i> Desr.
<i>Anagallis arevensis</i> L.	<i>Oxalis corniculata</i> L.
<i>Chenopodium album</i> L.	<i>Oxalis latifolia</i> HBK
<i>Chenopodium murale</i> L.	<i>Phalaris minor</i> Retz.
<i>Cirsium arevse</i> L. Scop.	<i>Poa annua</i> L.
<i>Convolvulus arvensis</i> L.	<i>Solanum nigrum</i> L.
<i>Coronopus didymus</i> L. Sm.	<i>Sonchus aleraeus</i> L.
<i>Cynodon dactylon</i> L. Pers.	<i>Sataria gaua</i> L., Beauv.
<i>Cyperus iria</i> L.	<i>Trianthema monogyna</i> L.
Weed diversity in the hills	
<i>Amaranthus viridis</i> L.	<i>Echinochloa cru-galli</i> L., Beauv
<i>Bindens pilosa</i> L.	<i>Melilotus indica</i> L., All
<i>Chenopodium Album</i> L.	<i>Oxalis corniculata</i> L.
<i>Chenopodium murale</i> L.	<i>Pennistum clandestium</i>
<i>Commelina benghalensis</i> L.	<i>Polygonum species</i>
<i>Cynodon dactylon</i> L., Pers.	<i>Setaria glauca</i> L., Beauv.
<i>Digitaria sanguinalis</i> L., Scop.	<i>Spergula arvensis</i> L.

weeds species in four different districts of Indonesia were *Amaranthus spinosus* L. (34.62 %), *Galinosoga parviflora* Cav. (29.66 %), *D. vilosa* (22.72 %) and *C. rotundus* (21.26 %) (24). In Egyptian experimental fields over two seasons, the predominant broadleaf weeds were *Medicago hispida* Gaertn., *C. album*, *Emex spinosa* L. and *Sisymbrium irio* L. The only narrow-leaved weeds recorded was *P. minor* (25). A weed flora study conducted in the Republic of Kosovo reported a total 67 species in potato fields, which were grouped into 58 genera and 26 families (26).

In a study conducted in Bulgaria, the structure of different weed diversity included *Xanthium strumarium* L., *Amaranthus retroflexus* L., *Solanum nigrum* L. and *C. album*, followed by some perennial types. Various types of weeds in Kenya fields, such as gallant soldier, *C. dactylon* and *Eleusine multiflora* Hochst. ex A.Rich., were reported in a study (27). The agronomic cultivation technologies significantly modified the frequency of mono- and dicotyledonous weeds species. The mabundant monocot weeds were *Echinochloa crus-galli* (L.) P.Beauv., *Setaria viridis* (L.) P.Beauv. and *Setaria glauca* (L.) P.Beauv. and occasionally *Poa annua* L. and *Avena fatua* L. The study also found two species of dicotyledonous weeds, namely *Anthemis arvensis* L. and *Cirsium arvense* (L.) Scop., in central-eastern Poland (28).

Critical period of crop-weeds competition in potato

Managing weeds throughout the development stages of the potato crop is crucial to prevent them from dominating and affecting crop growth (1). To maximise potato production, it is recommended to control weeds during the first 4 weeks after planting and it is essential to keep the crop free of weeds for 40–50 days (1). A study showed that the critical period of weed competition (CPWC) was around 1–1.5 months after planting in the plains (Punjab, Haryana, Delhi, Uttar Pradesh, Bihar and West Bengal). The CPWC for the hills was 1.5 to 2 months (Himachal Pradesh, Jammu and Kashmir, Assam, Sikkim, Meghalaya, Karnataka and the Nilgiris hills of Tamil Nadu) (19). After planting, dicotyledonous weeds populations increased for up to 6 to 7 weeks while monocotyledonous weeds populations increased for up to 6 weeks. Dicotyledonous weeds exhibited a higher density compared to monocotyledonous weeds.

The potato crop plant coverage across rows can lead to the emergence of new weeds at 65–70 days after planting (29). Although these later weed flushes may not significantly reduce tuber yield, they contribute to the weed seed bank. Further, they can cause

issues in subsequent years and can mechanically interfere with crop harvesting, thereby reducing marketable yield (1). Weeds serve as a major source of seed replenishment for future infestations.

Weeds management measures

Maintaining the population of undesirable plants at a minimum is the major goal of weed control to ensure that the intended tuber yields and farm earnings can be achieved. The selection of an appropriate weed management strategy depends on factors such as the severity of weeds infestation, their developmental stage and the economic conditions of the farming operation. Various methods for controlling weeds in potato cultivation have been described, including mechanical, cultural, chemical and biological techniques, along with integrated approaches.

Mechanical measures

To lessen the detrimental effects of weeds on yield and increase potato productivity, an effective weed management approach should be developed. In India, mechanical weeding remains the prevalent method of weed control, primarily due to the occurrence of small, fragmented landholdings and affordable labour. On small farms, basic methods such as hand pulling, cutting and hoeing are commonly used. However, on commercial farms, tractor tillage remains the predominant mechanical method for weeds management. The initial 4–6 weeks after emergence constitute the CPWC for ensuring that the potato crop gains a competitive advantage over weeds in the fields (30). The optimal time for inter-cultivation is typically 1 month after planting, when potato plants reach a stature of 10–12 cm. Hand hoeing is not very effective since, if performed in the later phases of plant growth, it may damage roots and disturb the root system. However, due to labour shortages during peak seasons and high labour costs, timely weed management practices may not always be achievable manually (31). In many regions of India, traditional methods such as khurpi, hand hoes and spades are still widely used for manually removing weeds from potato fields. This approach proves practical and effective as long as manual labour remains accessible and affordable. Moreover, these methods are particularly effective against annual and biennial weeds, as they prevent regeneration from vegetative fragments left in the soil after weeding operations.

Earthing-up (hilling) immediately after weeding and inter-cultivation helps retain soil moisture and ensures proper ridge formation. It significantly influences both the quantity and size of potato tubers while also reducing weeds populations. A 10–20 % increase in tuber production was observed when hilling was performed shortly after emergence compared to control treatments (32). This enhancement is attributed to optimal soil conditions during active tuber development, which facilitate better nutrient absorption and reduce competition from weeds, ultimately leading to higher tuber yield (33). In the Indian state of Punjab, blind weeding has proven helpful for early potato crops by preventing rapid growth of *Trianthema monogyna* L., which tends to cover the entire field before potato plants emerge. Research shows that hand weeding can increase potato tuber yield and net returns compared to herbicide application. Combining manual weeding with practices like hilling and herbicides such as isoproturon, metribuzine and pendimethalin, can result in similar levels of tuber yield. The lowest weed population and biomass were achieved by hand weeding in conjunction with hilling, which had a weed control efficiency ranging from 65–94 % (34).

In terms of decreasing weeds dry weight, boosting weeds control efficacy and enhancing tuber yield, weeding at 1 month with hilling was equivalent to pre-emergence treatments of herbicides such as atrazine and fluchloralin (1). Single hand weeding after 20 and 40 days of planting produced the highest potato yield (22 q/ha) and net profit (₹245677) (35). Proper soil mounding significantly boosts yields and reduces tuber greening compared to shallow planting (36). Early hilling in potato plants promotes greater tuber initiation and stolon establishment. Hilling at 2 weeks after sowing resulted in lower greening percentages (3 %) and higher percentages of marketable tubers (45 %) compared to control conditions (37).

Cultural measures

Weeds are difficult to control after they become established in the field, since checking weeds emergence, growth and development and propagation of weed seeds is usually easier and cheaper than controlling them after a significant invasion. Using high quality certified clean seed stock, clean farming equipment for planting, managing weeds along highways and controlling weeds on levees or bunds are some methods for preventing weeds invasion (38). Reducing soil disturbance by machinery, livestock and wildlife is essential to limiting the spread of noxious weeds. Crop seeds are frequently contaminated by weeds, particularly when the weed seeds closely resemble the crops in size and shape. Contamination occurs especially when weeds and crops have similar growth pattern and set seeds at the same time. By using certified seeds, clearing weeds out of ditches and fencerows before seeding and cleaning harvesting equipment before transferring it from one location to another, farmers may prevent weeds from sprouting up in their fields (39).

In agro-ecosystems, the soil serves as a seed bank since it contains all the viable weeds seeds that are the main source of

new infestations (40). A specialised weed flora becomes increasingly resistant to weed management methods due to monoculture and the repeated use of the same techniques over many years (41). It is recommended to use only fully decomposed manure (at least 4–5 months old material); otherwise, viable weed seeds may still enter fields through partially decomposed or unrotted manure. To prevent or restrict the entry of fresh weed seeds into the soil seed bank, several agronomic practices are often recommended. These practices include the use of certified seeds, avoiding the transportation of soil from weed-infested areas, cleaning mechanical tools and equipment before moving them from field to field and localised irrigation and fertilisation (42).

Enhancing crop competitive ability is a key method to overcome the germination and spread of the weeds (43). The significance of competitive varieties in weeds management increases when they are combined with agronomic modifications such as sowing date, crop density and spatial patterns. The use of highly competitive cultivars lowers labour costs and pesticide use in conventional agriculture and it is evident that this strategy is becoming increasingly crucial in organic production system (44). As shown in Table 2, these objectives can be accomplished by increasing crop competitiveness and decreasing the soil weed seed bank (43).

Weeds can be managed by effectively removing them and their propagules from the cultivated crop area without significantly hindering crop growth (45). The accumulation of weed seeds should be considerably reduced in a short period by carefully planning post-infestation weed control methods. Cultural practices, including crop rotation with potato, well-timed crop cultivation, the application of good agricultural practices that

Table 2. The primary outcome and overview of many cultural techniques used in the integrated weed control of potato

Action	Main effect	Description
(A) Soil weed seed bank control		
Good agronomic practices	Reduction in seed bank input	Adopt certified seeds with a high rate of purity; use well-composted manure; filter irrigation water; prevent moving soil from weed-infested regions; clean machinery and equipment before moving from field to field; and sanitise the field (including uncultivated areas) before weeds proliferate
Ploughing	Rise in seed bank output	Changing the seedbank's vertical distribution, ploughs can reduce the germination of weeds buried inside the soil and accelerate the physiological death and predation of weed seeds
A setup having intercropping, mulching, green manure and cover crops	Low frequency of weed appearance	Mulches suppress weed germination both chemically and physically, primarily through allelopathy
Crop rotation	Decline of germination and appearance of weeds	A specialised flora disrupted by the crop sequence's diversification, which keeps weeds from adapting and establishing. Instead, a diverse weed community made up of numerous species that are all present at low densities is created
Heat up the soil surface i.e., Soil solarisation	Decrease in the germination of weeds	By heating germinating seeds from 50 to 55 °C at a soil depth of 5 cm and raising the temperature to over 40 °C in the uppermost layers of the soil solarisation stops seed germination and induces dormancy in seeds
Stale seedbed	Less weeds occurrence	Early seedbed preparation, coupled with light irrigation, trailed by mechanical, physical, or chemical weed control measures, can effectively limit weeds emergence during the initial stages of crop development
(B) Enhance the capacity of crop against weeds		
Selection of weed-competitive cultivars	Increase soil cover efficiency at early growth stage	Selecting varieties with large leaf areas, high growth rates, early vigour, strong roots and allelopathic potential
Crop density	Accelerated rates of soil cover in the initial phases	The crop benefits from weed-crop competition when crop density is increased and row spacing is decreased
Spatial patterns and plant arrangement	Enhancement of agricultural competitiveness over the entire cycle	Weeds can be choked out by using techniques like twin-row systems, bidirectional seeding and narrow-row spacing
Crop planting/sowing date	Early-stage increases in crop competitiveness	When crops are planted or sown when the weather is at its most favourable, they can emerge or germinate before weeds and have a higher chance of competing with them for different forms of energy
Transplanting	Early-stage increases in the crop competitiveness	While comparing to seeded crops, transplanting crop have a limited short time period and easier different method of weeds control

Source: Ref. (43).

encourage robust crop growth and the use of well-adapted varieties, can all contribute to an efficient weed management programme (6).

Weeds development can be efficiently suppressed by the potato crop itself once the rows are closed. Higher crop densities and tighter row spacing often benefit the crop by influencing weeds-crop competition, which reduces biomass and weeds emergence, especially in the early phases of crop growth. On the other hand, excessively high crop density can cause intraspecific competition, reduce yield and make it more difficult to employ weeding techniques (46). A shift in plant arrangement (such as twin-row systems, bidirectional sowing, etc.) helps suffocate weeds. The timing of crop planting significantly influences the types and timing of weeds emergence. Choosing a planting or sowing date that aligns with favourable weather conditions promotes quick germination and emergence of the crop (47). Effective weed suppression can also be achieved by maintaining robust, healthy potato plants in the field. Due to labour costs and the expense of preparing mulch, non-chemical weeds management methods may be more expensive than chemical-based ones; however, ecological alternatives, including the application of plant residues, may be more environmentally benign. The use of herbicides is detrimental to the health of people, animals and soil organisms (48). Hence, an appropriate strategy is needed to prevent severe weeds infestations and unmanageable competition with the growing crop.

Mulching is a common practice in potato cultivation, as it significantly boosts yield in terms of both quantity and quality (49). It is important because, compared to bare soil, plant growth is often greater when mulch is applied. Mulching can be carried out using black or silver plastic and organic materials such as straw, husk and cover crops, which offer one or more ecological functions including protecting the soil, enriching it, deterring pests and increasing crop yield (50). Different coloured mulches possess varying optical properties. The efficacy of plastic mulches varies based on the colour of the plastic, for instance, black, white, brown, blue, red and green (51). Organic mulch applied at sowing has been shown to decrease weed plants in potato; however, weeds are less affected by straw mulch applied after cultivation (52). Potato yield and weeds suppression were not significantly affected by low volumes of straw mulch (2–5 t/ha), whereas straw mulch applied at a rate of 6 t/ha and 30 days after planting enhanced potato production (53). Different types of mulch help to slow down the water evaporation and assist preserving a proper soil microclimate (53). These low-cost and safe techniques demonstrate superior weed control and result in high tuber production and quality of potato plants, along with improved growth characteristics.

A thorough crop rotation can disrupt weed life cycles and prevent certain species from outcompeting the main crop. When crops and weeds have the same life cycles, it becomes more challenging for weeds to emerge as a major issue. The addition of cool season annual crop to the crop rotation helps to decrease the population density of summer annual weeds (54). Green manure crops like cowpea and dhaincha, or at least 24 months crop rotation strategy in a given area, can effectively suppress weeds by smothering them. This practice enriches the soil's organic carbon content and reduces the unwanted plant species (1). The 3-year or longer rotation is particularly beneficial for cultivating potatoes, as

it enhances the crop's competitiveness against weeds compared to a shorter 2-year rotation. Additionally, longer rotations can also lead to reduced populations of diseases, insects and nematodes.

Intercropping can enhance weeds control effectiveness compared to monoculture in two main ways. First, intercrops may divert resources away from weeds or inhibit their growth through allelopathy, resulting in higher crop productivity and lower weeds biomass (55). Alternatively, intercrops might utilise resources that are unavailable to weeds or use resources more efficiently, leading to increased yield without reducing weed growth below thresholds levels, as observed in monoculture crops. It was found that potato intercropping with legumes such as *Vigna radiata* (L.) R.Wilczek, *Lathyrus sativus* L., *Cicer arietinum* L. and *Pisum sativum* L. resulted in significant suppression of weeds biomass and higher benefit-cost ratios, especially when potatoes were intercropped with *P. sativum* (54).

Soil solarisation and the stale seedbed are two further preventive measures used to lower the weeds seed bank. In solarisation, the soil surface layers can reach temperatures of above 40 °C at a depth of 5 cm and up to 50–55 °C (56). Many soil-borne pests and weed seeds die at these temperatures because it prevents their germination. Soil solarisation is an effective method which involves covering moist soil with transparent or black polyethylene plastic sheet during the summer months for a minimum of 6 weeks (57). The heat, moisture and direct contact with the plastic create conditions that effectively kill weed seedlings through heat stress. In northern regions, solarisation using polyethylene sheets can elevate soil temperatures to 50–60 °C, significantly reducing major weeds compared to non-solarised soil (58). Different methods of soil solarisation are equally effective in managing weeds, achieving reductions in weeds biomass ranging from 94–99 % and decreases in weed count by 86–94 % compared to the control (59). This approach can be particularly beneficial for high-value potato cultivation, such as seed potatoes. Research has found that the minimum weed count and dry weight were achieved when transparent polyethylene films having 0.05 mm and 0.10 mm thickness were used for 4–5 weeks following groundnut cultivation, with or without conventional or chemical weeds control (50). Utilising the hot, dry summer months is crucial for desiccating weeds. It is recommended to carry out two to three deep field cultivations during this period to effectively control both annual and perennial weed such as *C. dactylon* (1).

The stale seedbed method is widely used to control weed infestation. This method involves creating a fine seedbed, allowing weeds to germinate and then promptly removing weeds seedlings through light cultivation before actual crop planting. Adequate soil moisture is required for weeds growth, which can be managed through irrigation. After that, the moist, weed-free soil can be used to plant crop seeds or transplants (1). The stale seedbed can be repeated two or three times before planting, if time permits (60). Weeds species that are particularly sensitive to the stale seedbed typically require light to germinate, have low initial dormancy and are found on or near the soil surface. Examples of such weed species include *Eclipta prostrata* (L.), *Digitaria ciliaris* (Retz.) Koel, *Leptochloa chinensis* (L.) and *Cyperus iria* L.

Chemical measures

Successful implementation of a chemical weed-control programme hinges on careful consideration of factors such as the types of weeds present in the field, soil characteristics, irrigation, tillage methods

and crop rotation. It is crucial to control young weeds chemically at an early stage because they are most susceptible at this time; otherwise, they become difficult to manage at later stages (61). A three-stage herbicide application strategy includes application a few days before plant emergence and again when crop plants have 2–4 leaves and attain a height of 10–15 cm (62). The shallow soil of ridges needs to be as fine and loose as possible to facilitate even application of herbicides. When inclement weather makes pre-emergence herbicide treatment impossible, post-emergence herbicide applications are typically necessary (61). Metribuzin, atrazine, pendimethalin, alachlor, diuron, metolachlor, rimsulfuron and isoproturon are commonly used herbicides for pre-emergence, while fluchloralin and EPTC (S-ethyl dipropyl thiocarbamate) are used for pre-planting applications in potato production (63). For post-emergence weeds control, paraquat, propanil and metribuzin are frequently employed.

Pre-emergence herbicides are crucial for providing optimal growing conditions to potatoes early in the growing season (64). Metribuzin is currently the predominant herbicide utilised in potato cultivation. It was the first herbicide widely used in potato farming and well-known as triazinone. Metribuzin, which is applied after 5 % potato plant emergence, is the most used herbicide for this purpose. After the crop has fully emerged, no herbicide can be used on potato crops (1). The weeds-free treatment with metribuzin applied as a pre-emergence at a rate of 0.75 kg/ha produced the best yield of potatoes (20 t/ha). The bio-efficacy of metribuzin was shown to be superior to that of the other treatments (22).

Two years of trials were conducted to study the efficacy of herbicides and integrated use of mulch with herbicides in controlling weeds in potato crop at Ludhiana, north-west India, during autumn 2016 and 2017. The pre-emergence application of metribuzin at 0.75 kg/ha was found effective in controlling weeds at different crop stages in potato. At 25 and 55 days after planting, the weeds density was 2.0 and 2.4 weeds/m² and the dry biomass of weeds was 1.6 and 1.4 g/m² respectively. Maximum tuber yield, consistent and efficient weeds control and financial gains were achieved by applying clodinafop and metribuzin at a rate of 195 g/ha post-emergence (64). The pre-emergence application of atrazine at a rate of 250 g/ha has demonstrated superior effectiveness in controlling both monocot and dicot weeds. This application method achieves a weeds control efficiency of 99 % and offers the highest benefit-to-cost ratio (63). At ICAR-CPRS (Indian Council of Agricultural Research-Central Potato Research Station) Gwalior, propaquizafop, sulfosulfuron and bentazone were evaluated for their effectiveness on potato crops. Propaquizafop, in various dosages, was found ineffective in controlling potato weeds, particularly *Chenopodium* sp. Sulfosulfuron remained a very effective herbicide for controlling weeds; however, it was not suitable for the potato crops because it caused yield reduction at all tested dosages due to phytotoxic effects among four potato varieties i.e. Kufri Jyoti, Kufri Chandramukhi, Kufri Lauvkar and Kufri Sindhuri (65).

A study conducted at Vegetable Research Centre, Uttarakhand found that pre-emergence application of metribuzin at 0.75 kg a.i./ha was effective for weeds control, whereas, total number of monocot weeds (41.0) and dicot weeds (1.0) were

found minimum under treatment weeds-free and post-emergence application of metribuzin at 0.75 kg a.i./ha at 60 days after planting (66). The pre-emergence application of atrazine at 250 g/ha was efficient in controlling monocot and dicot weeds with 99 % weeds control efficiency compared to a mixture formulation of atrazine at 125 g/ha and metribuzin at 175 g/ha as pre-emergence and post-emergence application of paraquat at 35 g/ha (67). A field experiment conducted on potatoes over three consecutive years and concluded that herbicide metribuzin at 0.75 kg/ha can be used as an effective herbicide for the management of weeds in potato cultivation under the southern dry zone of Karnataka (68). The early post-emergence application of metribuzin at 0.30 kg/ha and pre-emergence pendimethalin at 0.60 kg/ha, followed by hilling at 45 days after planting, was found to be an effective measure for weeds control in potatoes. Resistance to triazine herbicides, including metribuzin, has been observed in 69 species globally. This resistance underscores the need for integrated weeds management strategies to effectively control weeds (1).

The pre-emergence application of prometryn 50 wettable powder (WP) at 0.75 and 1.0 kg a.i./ha was found effective in controlling the monocot and dicot weeds in West Bengal, India. An experiment conducted on the potato crop at Banaras Hindu University, Varanasi, Uttar Pradesh, India, concluded that the application of paraquat dichloride (24 % soluble liquid (SL)) at 2.0 L/ha effectively controlled different types of weeds (69). Better results were obtained by using pendimethalin at 2 L/ha and alachlor at 3 L/ha in potatoes. Ethoxysulfuron, sulfentrazone and halosulfuron are excellent herbicides for controlling cyperaceous weeds such as *C. rotundus* (70) and oxadiazon for *Oxalis* spp. (71). Both sulfentrazone and halosulfuron have been widely studied worldwide in potato crops for weeds management (72).

Researchers conducted a study to investigate the phytotoxic action of various herbicides on potato cv. agata under Brazilian conditions. Isoxaflutole and clomazone have broader spectrum control of grasses when used at doses of 360 and 75 g/ha, respectively; flumioxazin is registered to control the growth of eudicotyledons at a dose of 35 g/ha in potato crops (71). According to other studies, flumioxazin has been found to be an effective herbicide for potato crops in controlling *Solanaceous* species (73), with selectivity at doses up to 72 g/ha (74). The mixture formulation of pendimethalin (30 EC) and clomazone (15 EC) at 450 and 225 g/ha, respectively, was found effective in controlling the monocot and dicot weeds, significantly reducing weed density and creating a weed-free environment for a longer period (75). Clomazone, a novel chemical herbicide, has been shown to control grass and broadleaf weeds in potato crops, although it may cause some phytotoxic symptoms in potato leaves. Research indicates that clomazone not only enhances tuber sugar and starch content but also increases yield. This herbicide represents a promising alternative to metribuzin and can be integrated with non-chemical strategies for effective weeds management in potatoes (76).

To manage diverse weeds species effectively, it is recommended to use appropriate tank combinations or successive applications of herbicides with different modes of action. This approach helps to check or slow the expansion of

herbicide-resistant weed population by targeting the same weed species through multiple modes of action. Customising herbicide tank mixtures according to the specific weed species present in each field enhances weeds control while maintaining the integration of cultural, mechanical and herbicidal methods. Precise field history information is essential when choosing the right tank mixtures and applying them in sequence. Examples of effective herbicide mixtures include pendimethalin plus rimsulfuron, pendimethalin plus metribuzin, metribuzin plus rimsulfuron and pendimethalin plus metribuzin plus rimsulfuron. Additionally, separate pre-emergence applications of metribuzin and pendimethalin in potato fields have also been employed. While developing a chemical solution for weed control, several factors require careful consideration, such as application techniques, timing of application and selection of an appropriate chemical. A lack of proper methods can damage crop growth. Other factors related to herbicide use, such as long-term negative effects on soil, crop residue, environmental impact and health risks to users, should also be comprehensively evaluated.

Biological measures

Biological control methods harness pathogens, parasites, predators and allelopathic agents with the primary objective of employing natural enemies to suppress weeds populations below economic thresholds in crops. Widely used synthetic herbicides pose significant environmental and public health risks because of their non-target toxicity, pollution potential, carcinogenic properties and mutagenic effects when extensively applied. In contrast, naturally occurring biologically active substances derived from higher plants offer comparable or even superior effectiveness to synthetic herbicides. Moreover, these natural plant molecules are biodegradable and target-specific, thereby posing fewer risks to the environment and public health (77).

A strategy was explored to reduce weeds intensity by leveraging both herbicide-induced stress and arthropod herbivory synergistically (78). In the US fluroxypyr dose-response bioassays were performed, both with and without the Colorado potato beetle (*Leptinotarsa decemlineata*) present on the volunteer cultivar Russell Burbank. Leaf area, tuber amount and shoot weight were all lower in the presence of herbivory than in its absence and herbicide use was reduced by 65–85 % when herbivory was added. Eighteen isolates from 9 genera of the alien, invasive weeds *Chromolaena odorata* were recovered from sick portions of the plant (79). A "natural product" was described as a substance that is derived directly from plant or animal products, rather than being artificially created. These herbicides are much safer and superior to synthetic ones. The following non-synthetic herbicides can be used to suppress weeds: acetic acid, citric acid, corn gluten meal and Matran II. Cinmethylin, derived from certain sage species, effectively suppresses annual grasses and broad-leaved weeds (80).

Integrated weed management (IWM)

Integrated weed management (IWM) is a comprehensive tactic for weeds population management which incorporates various strategies to provide crops with a competitive edge over weeds (35). The IWM can reduce the selection pressure for weeds resistance to herbicides, minimise the negative environmental effects of some weeds methods, maintain sustainable agricultural systems and control weeds populations at levels that are manageable. This system integrates all available mechanical, cultural, biological and

chemical weeds control strategies and its applicability depend upon various factors like type of weeds species, meteorological conditions, irrigation techniques, soil structure and texture and socioeconomic limitations. Therefore, an IWM programme needs to be modified every year and in line with the specifications unique to each situation.

The field experiments were conducted during rabi seasons 2006 and 2007 at research farm of Uttar Banga Krishi Viswavidyalaya, as well as through participatory approach at Khagribari, Cooch Behar, West Bengal to find out effective and economical weeds management practices in potato. Mulching exhibited the highest weed control efficiency and the lowest weeds index values among different weeds management techniques. Pendimethalin at 0.60 kg/ha and metribuzin at 0.30 kg/ha were next in line. Mulching, pendimethalin at 0.60 kg/ha and metribuzin at 0.30 kg/ha produced yields comparable to weeds-free check. Following seed tuber planting in ridges, mulching with rice straw significantly enhanced tuber output, reaching 17 % at the research farm and 12 % at farmers' fields compared to manual weeding (81). Based on research conducted at Ethiopia, effective weeds management strategies in potato fields include applying isoproturon pre-emergence at 2 kg/ha followed by pendimethalin at 1.5 kg/ha. Alternatively, manual weeding twice at 20 and 40 days after emergence is considered an optimal option (82).

Metribuzin at a rate of 400 g/ha combined with mulching had the same effect as metribuzin at a rate of 800 g/ha, reducing the overall weeds density to 19 plants/m². Metribuzin applied at 400 g/ha effectively decreased weed density by 19 and 10 plants/m², respectively, when used in conjunction with one or two hoeing (83). According to a study at Munshigonj, Bangladesh, the organic mulch (water hyacinth) when applied with herbicide Ronstar (25 electrical conductivity (EC)) at 1 mL/L of water, 1 week after planting, controlled the weed population by up to 94–95 % 1 month after planting compared to the treatment with mulch alone. It was also observed that two hand weeding at 3 and 6 weeks after planting were the most effective treatments for reducing weed number and dry weight while improving crop growth. This was followed by manual weeding once at 20 days after planting, combined with straw mulch application at a rate of 5 t/ha at 25 days after planting (35). In north-west India, an integrated approach involving the application paddy straw mulch at a rate of 6 t/ha along with a post-emergence spray of 195 g/ha of metribuzin and clodinafop allowed for consistent weeds suppression, the highest possible tuber yield and the highest possible economic returns. In the absence of paddy straw, potato weeds can be effectively managed by spraying a pre-mix formulation of clodinafop with metribuzin at 260 g/ha at 20 DAP (76).

Artificial intelligence (AI)

Precision agriculture harnesses integrated technologies such as digital instruments, sensors and data systems to enhance crop productivity while reducing adverse environmental effects (84). Recent advancements in nanotechnology, sensors, robotics and computing hardware, have significantly contributed to the rapid advancement of precision agriculture over the past decade (18). These technologies enable precise monitoring and documentation of weeds species present in the field (85). Unmanned vehicle systems (UTVs) are platforms that can be used for both terrestrial and aerial applications. They provide several specific advantages such as

precision, labour reduction, spatial accuracy and environment friendly for managing and executing agricultural tasks (86). Unmanned aerial vehicles (UAVs) are one of the most widely employed technologies in precision agriculture and highly valuable for site-specific weed management (SSWM) because of their capability to provide precise and environmentally safe weeds control methods (67). Unmanned aerial vehicles (UAVs) enable continuous monitoring and mapping of weed infestations with high precision, which contributes to effective weed population control (87). The integration of GPS technology for accurate field mapping and UAVs equipped with advanced cameras and sensors further enhances their utility in agriculture (88). This combination allows UAVs to swiftly and precisely monitor large agricultural areas, identifying individual weeds and enabling targeted management strategies (89). Overall, UAVs play a crucial role in modern agriculture by facilitating SSWM practices that optimise resource use, reduce environmental impact and enhance overall crop health and productivity.

Site-specific weed management (SSWM) has become increasingly popular because of rising labour costs and growing concerns about health and the environment. The first crucial step in implementing SSWM is the accurate detection, identification and targeted removal of weeds in the field. Various methods for weeds detection are illustrated in Fig. 1 (88). Several robotic weeders have been developed globally to address these challenges:

1. Tom, Dick and Harry: These robots are designed to minimise herbicide use. Tom digitally maps the field and locates each plant, Harry plants seeds and tracks their growth, while Dick uses electricity to electrocute weeds (88).
2. Laser Weeder: Designed for row crops on large land areas ranging from 200 to 10000 acres, this robot replaces multiple manual labourers and can cover 15–20 acres per day (88).
3. EcoRobotix: Developed in Switzerland, this prototype specialises

in spot thinning and weeding. It features a computer system for weeds recognition and utilises a solar-powered battery for herbicide application (90).

4. TerraSentia: A small agricultural robot developed for autonomous weeds identification, enhancing precision in weeds management tasks (91).
5. BoniRob: Developed by Bosch Deepfield Robotics, this invention automates planting and weeding tasks, reducing labour-intensive processes in agriculture.

These robotic weeders showcase advancements in technology aimed at reducing reliance on herbicides, improving efficiency and promoting sustainable agricultural practices. As technology continues to evolve, these innovations play a crucial role in achieving effective and environmentally friendly weed management strategies. Various robotic weeding implements are increasingly entering the marketplace, although many are currently designed to target specific weeds and crops (88). However, high cost remains a limiting factor in the widespread adoption of robotic weeding systems.

Multispectral cameras such as red, green and blue (RGB) are effective in detecting weed patches in potato crop. The efficiency of these cameras depends on factors such as camera resolution, shutter speed, aperture value, flight altitude and the specific UAV used during operation. Research has shown that cameras operating under these three factors can identify weeds species with high precision when properly utilised in conjunction with UAVs (92). Unmanned aerial vehicles (UAVs)-mounted cameras have been particularly effective in identifying various types of weeds, including monocotyledonous species such as *Avena* spp., *Phalaris* spp. and *Lolium* spp., as well as dicotyledonous weeds like *C. album*, *A. palmeri* and *C. arvense* (93). These systems are capable of implementing targeted weeds management strategies using herbicide spraying or mechanical techniques and can train algorithms used by autonomous weeding robot systems through advanced image analysis, computer vision, deep learning (DL) and

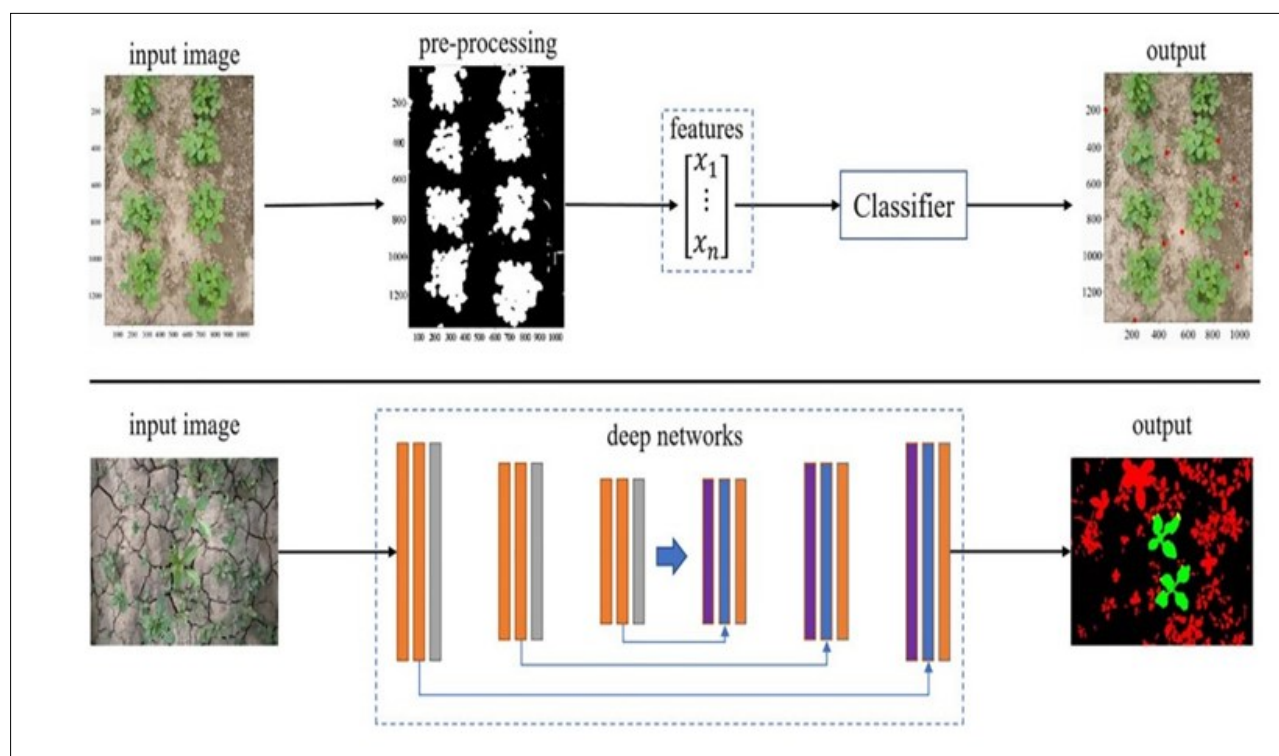


Fig. 1. The distinction among (a) deep learning (DL) (b) machine learning (ML). Source: Ref. (87).

geo-positioning (GPS) technologies. To advance quickly in this field, a solid scientific and technical understanding of specific objectives and available technology is essential (94). This includes optimising camera and UAV configurations, developing robust algorithms for weeds detection and management and integrating these technologies effectively into precision agriculture practices to enhance overall crop health and productivity while minimising environmental effects.

Convolutional neural networks (CNNs) can be applied to image classification, object recognition and fine-grained categorisation (95). Artificial neural networks and digital cameras have shown rapid progress and offer new tools and techniques for weed and crop management (32). A pool of 93000 images was used to adapt and train three distinct CNNs: ResNet-50, Xception and VGG16 (96). Each image represented a single plant species in the training dataset. Upon analysis of the images, weeds species identification and plant recognition achieved a Top-1 accuracy ranging from 77–98% (32).

The “potato weed manager” is a user-friendly decision support application that uses images to assist growers and extension workforce in selecting the most effective weed control methods for their specific crop conditions. This tool considers variables such as farm location, primary weeds species, other associated weeds and crop development stage. Hosted at <http://cpri.ernet.in>, this decision support system (DSS) provides professional guidance on potato weed management without the need for on-site expertise. It is freely accessible (97). The application recommends the use of approved herbicides such as pendimethalin, fluchloralin, atrazine, alachlor, isoproturon, methabenzthiazuron, metribuzin, simazine and oxyfluorfen, applied at appropriate doses for effective weed control in potato crops (98).

The DSS provides recommendations for weed management based on the stage of crop development (Fig. 2). Before planting, the DSS may recommend suitable pre-planting weeds management

strategies. If plant emergence is less than 5 %, it typically suggests pre-emergence weed management methods. Once the crop has emerged, the DSS offers guidance on effective post-emergence weed control strategies. The support system adapts its recommendations depending on the specific stage of crop growth and the presence of weeds in the field. This ensures that appropriate weed management practices are implemented at each phase, optimising weeds control efforts and minimising potential competition with the crop (97). A farmer may decide to choose a suitable weed control strategy based on different crop stages by taking into consideration the available resources and crop stage (99).

By utilising AI tools for weeds management, farmers can achieve more precise and efficient control of weeds while minimising the use of herbicides. This approach not only improves crop health and productivity but also supports sustainable farming practices by optimising resource utilisation and reducing environmental effect. As technology continues to advance and costs potentially decrease over time, the commercial viability and adoption of AI systems are expected to increase, offering significant benefits to agriculture globally. In recent years, precision farming techniques such as on-the-spot herbicide spraying, robotic weeding and precise mechanical weeds management have advanced significantly.

Biotechnology-assisted weeds management approaches

Despite ongoing efforts to improve current methods for managing weeds in agriculture, it is essential to acknowledge the pressing requirement for innovative weed control techniques (99). Rather than addressing weeds only after emergence, the goal of weed management should focus on effectively controlling their populations and reducing the global seed bank. Future advancements in weed control could potentially benefit from various genetic strategies illustrated in Fig. 3, which integrate genomics and biotechnological approaches, tailored to either crop or weed species depending on the specific objectives (100).

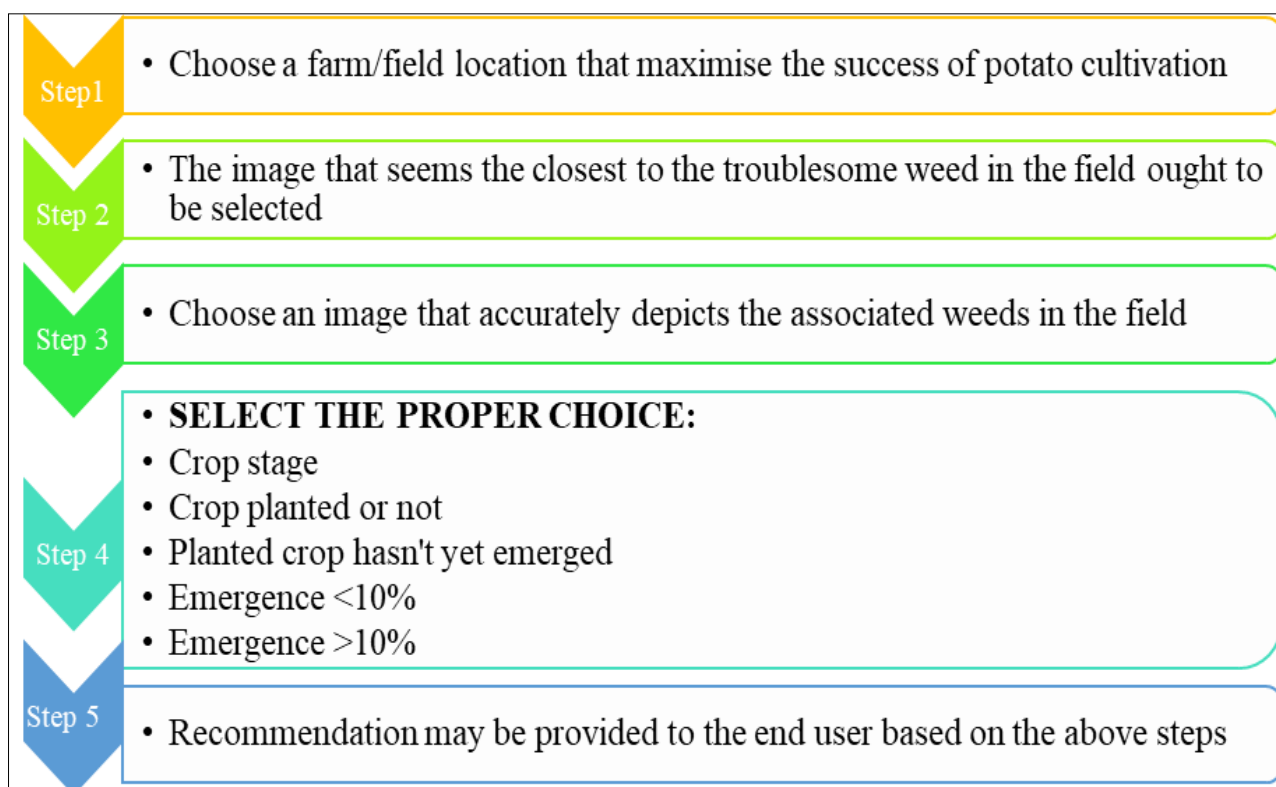


Fig. 2. Strategy for weed management.

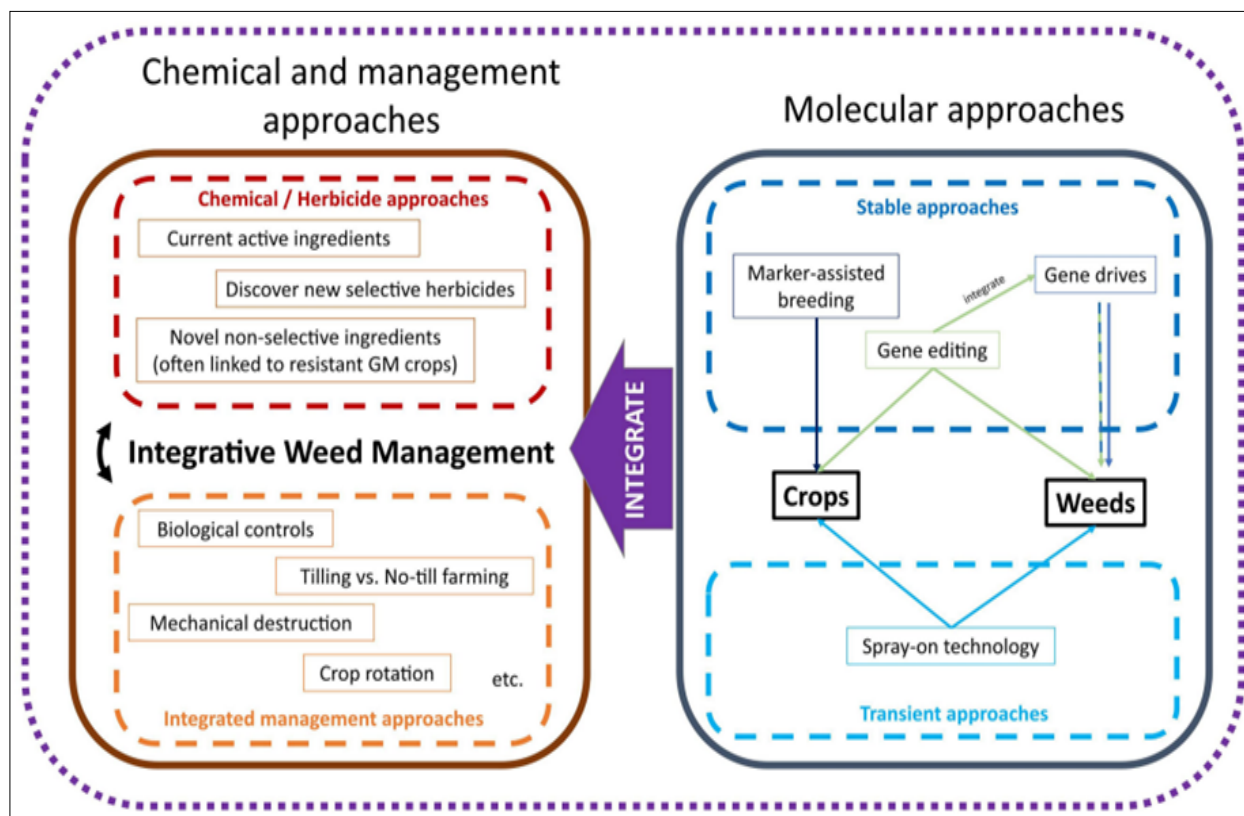


Fig. 3. A theoretical structure for creative weed control. Source: Ref. (99).

Direct genetic control approaches show promise for weeds management in agricultural systems. Recent advances in “omics” and less expensive sequencing technologies, coupled with the introduction of CRISPR/Cas9 gene-editing systems, have added to this promise. Both temporary and permanent controls are possible (11). Recently, CRISPR/Cas9-derived cytidine base editors (CBEs) were developed to facilitate the conversion of C to T bases. The most common method in dicotyledonous plants is stable genomic integration of CRISPR/Cas9 components via *Agrobacterium*-mediated transformation. However, it can be challenging to completely eliminate foreign DNA, particularly in vegetatively propagated plants. *Agrobacterium*-mediated transformation was used with a CBE to target the acetolactate synthase (ALS) gene in tomato and potato. The targeted cytidine bases were effectively and efficiently edited, resulting in plants resistant to chlorsulfuron and with a precise base editing efficiency is up to 71 % in tomato. More notably, it generated 13 % and 10 % edited, non-transgenic plants in the first generation of potatoes and tomatoes respectively (81).

To reduce the vigour of weeds, various technologies are now being employed, including gene drive, transient technology and the targeting of specific genes such as those from the Cytochrome P450 family and herbicide target genes. These efforts also encompass genes related to plant growth regulation, seed dormancy, sex determination, flowering time, seed shattering and modification of root exudate profiles. These strategies encompass a broad spectrum of technologies that can be utilised to diminish the fitness and competitiveness of weeds or enhance crop competitiveness or tolerance to herbicides. A recent study demonstrated significant yield increases of approximately 50 % in rice and potatoes through the expression of the human RNA demethylase fat mass and obesity-linked gene. However, it is important to note that such techniques fall under the category of

genetically modified (GM) organisms and are subject to corresponding regulations. While there are many technological, practical and regulatory obstacles to overcome before these promising molecular technologies can be used for weeds management. Further, the desire to lessen or eliminate the use of chemicals in agricultural areas has given rise to even more motivation to create workable and viable molecular solutions (99, 100).

Conclusion

The unwanted plant species commonly referred to as weeds are a major biological constraint affecting crop production and productivity in agro-ecosystems. Effective weed management in conventionally grown potato crops often requires a combination of strategies such as stale seedbed techniques, weeds threshold management, direct interventions, soil solarisation and judicious herbicide use, supplemented by advancements in artificial intelligence (AI) tools and biotechnology. The IWM strategy has developed as a comprehensive approach to meet the demand for sustainable weeds control strategies that are both economically viable and environment friendly. The flexibility of IWM is crucial for adapting to changing socio-economic and environmental factors over time. Integrating diverse control methods presents significant challenges and necessitates ongoing research support. Herbicide usage often increases due to an inadequate understanding of weeds dynamics and limited practical alternatives for weeds management. Future research directions should focus on enhancing crop competitiveness against weeds through traits such as improved seed vigour and optimised canopy architecture in varieties and hybrids. Developing herbicide-tolerant crop cultivars remains one of the most effective weeds control strategies. Additionally,

advancements in low-cost, high-efficiency herbicide application technologies, including adjuvants, carriers and spray equipment, are critical for reducing costs and maximising herbicide effectiveness and precision delivery systems. There is a growing need for investment in weeds research through improvements in AI and next generation biotechnological tools to further enhance weed management practices in agro-ecosystems.

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Authors' contributions

YC, DS and AS carried out the conceptualisation; YC, DS, A and VK prepared the original draft; DS, SKD and IA conducted the review and editing; YC, TM and D completed the visualisation and PK carried out the revision. All authors have read and approved the final manuscript.

Compliance with ethical standards

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