Nonconventional Weed Management Strategies for Modern Agriculture

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Weeds are a significant problem in crop production and their management in modern agriculture is crucial to avoid yield losses and ensure food security. Intensive agricultural practices, changing climate, and natural disasters affect weed dynamics and that requires a change in weed management protocols. The existing manual control options are no longer viable because of labor shortages; chemical control options are limited by ecodegradation, health hazards, and development of herbicide resistance in weeds. We are therefore reviewing some potential nonconventional weed management strategies for modern agriculture that are viable, feasible, and efficient. Improvement in tillage regimes has long been identified as an impressive weed-control measure. Harvest weed seed control and seed predation have been shown as potential tools for reducing weed emergence and seed bank reserves. Development in the field of allelopathy for weed management has led to new techniques for weed control. The remarkable role of biotechnological advancements in developing herbicide-resistant crops, bioherbicides, and harnessing the allelopathic potential of crops is also worth mentioning in a modern weed management program. Thermal weed management has also been observed as a useful technique, especially under conservation agriculture systems. Last, precision weed management has been elaborated with sufficient details. The role of remote sensing, modeling, and robotics as an integral part of precision weed management has been highlighted in a realistic manner. All these strategies are viable for today's agriculture; however, site-specific selection and the use of right combinations will be the key to success. No single strategy is perfect, and therefore an integrated approach may provide better results. Future research is needed to explore the potential of these strategies and to optimize them on technological and cultural bases. The adoption of such methods may improve the efficiency of cropping systems under sustainable and conservation practices.

Key words: Allelopathy, biotechnology, crop nutrition, herbicide resistance, precision agriculture, weed management.

Population explosion during the last few decades has exerted immense pressure on crop production, forcing the farming community to intensify agriculture to meet food demands. Weeds are a major factor causing reduction in crop yields through competition and allelopathic interactions. In modern-day agriculture, weed infestations and weed behaviors frequently change because of intensive management practices, climate change, and ecological shift (Chauhan et al. 2006, 2014). As a consequence, the existing management options need to be altered to ensure effective control given these shifts. In developing countries, manual or mechanical weed management is more prevalent, whereas in developed and technologically advanced regions, chemical weed management is dominant

(Chauhan 2012; Chauhan and Gill 2014). The difference in management practices depends on labor and resource availability (Zimdahl 2013). Today's agriculture requires a modified weed management regime to cope with the problems associated with traditional techniques (Bajwa 2014). Ecology-based and nonconventional weed management tools may offer solutions to aggravating problems of herbicide resistance, environmental pollution, weed diversification, biological invasion, and yield losses (Chauhan 2013; Chauhan and Johnson 2010; Chauhan et al. 2010; Singh 2007). Keeping in view these problems and potential opportunities, nonconventional and nonchemical weed management strategies like improved tillage, crop nutrient management, weed seed predation, allelopathy, herbicide-tolerant crops, bioherbicides, thermal techniques, and precision weed management have been discussed comprehensively in this review.

The importance of modified tillage in weed management has been reviewed by several researchers (Bajwa 2014; Brainard et al. 2013; Chauhan et al. 2012; Chauhan and Gill 2014). Walsh et al. (2013) comprehensively reviewed the weed man-

agement potential of harvest weed seed control. Their key recommendations have been highlighted in this review and the missing links have been elaborated. Impact of fertilizer management on weed dynamics is a relatively neglected aspect (Bajwa et al. 2014; Blackshaw and Brandt 2008), but this review provides an insight into this subject. Some classic reviews on the role of allelopathy in weed management have been published over the years (Bhadoria 2011; Cheema et al. 2013; Farooq et al. 2011, 2013; Nawaz et al. 2014; Weston and Duke 2003; Worthington and Reberg-Horton 2013). The practical implications, latest scenario, future research needs, and the scope of allelopathy in integrated weed management strategies have been thoroughly discussed in this review. Different reviews have concluded that the development of herbicide-tolerant crops has revolutionized the crop production in many regions (Beckie et al. 2006; Dill et al. 2008; Duke and Powles 2009; Green 2012). Although biological weed management is not a panacea under prevailing conditions, it has a great potential (Ash 2010; Charudattan 2001, 2005; Hallett 2005). Meanwhile, the advancements in technology have created vast opportunities for weed management in the form of thermal techniques, including flaming, solarization, electrocution, and microwave technology (Bond and Grundy 2001; Knežević et al. 2011; Rask and Kristofferson 2007). Precision weed management is another prospect of modern weed management. The application of remote sensing, modeling, and robotics in a very sophisticated and highly scientific manner (Christensen et al. 2009; Freckleton and Stephens 2009; Lamb and Brown 2001; Slaughter et al. 2008; Thorp and Tian 2004; Torres-Sanchez et al. 2013; Young et al. 2014) will enable us to pave/tread excellent paths for a site-specific, efficient, targeted, and economical weed management in the future.

No doubt, each and every weed control strategy has some unique benefits, but under the current agriculture scenario, an overall shift toward more sustainable and targeted practices is inevitable. In this review, a detailed and comprehensive analysis of these potential strategies has been done, which will help weed scientists to view the comparative efficacies and potential implications of these alternative nonconventional strategies, primarily avoiding use of the synthetic chemicals. To the best of our knowledge, a comprehensive review of all these potential nonconventional weed management strategies leading to a fruitful effort for integrated weed management under the present

and future conditions on a sustainable basis has not been presented previously.

Improved and Targeted Tillage

Tillage plays an important role in weed control and has been used as an effective management tool since ancient times. Tillage is still very effective, as different types of modern cultivators and weeders are facilitating mechanical weed management (Wallace and Bellinder 1992). The advent and successful adoption of no-till systems using herbicides have shown that tillage is not as necessary for crop production as it is for weed control (Zimdahl 2013). Tillage has significant impact on the efficiency of soil-applied herbicides, particularly dinitroanilines (Singh et al. 2012); higher water volume is required to improve the efficacy of PRE herbicides under zero-tillage systems (Borger et al. 2013).

Tillage Implements for Weed Management. Appropriate tillage implements are needed for an effective weed control. In ancient times, bullocks/horses were used to move different types of cultivators, sweeps, and hoes for weed eradication. Since the advent of mechanized farming, the trend of using tractor-mounted equipment has increased. Tractor-mounted equipment is easier to use under conventional tillage systems but more difficult in modified tillage systems, including no-till, strip tillage, and other conservation tillage systems because of retained residues (Brainard et al. 2013). Residue mulches or living cover crops can be managed through mowing or use of a high-residue cultivator (Creamer and Dabney 2002). Some important mechanical weed-management tools include the use of a rotary hoe, rototiller, rotavator, power tiller, rod weeder, cultipacker, spring tine harrow, finger weeder, torsion weeder, brush weeder, spike-tooth weeder, and pneumatic weed blower (Duerinckx et al. 2005; Mohler et al. 1997). Murphy et al. (2006) compared moldboard-plowed, chisel-plowed, and no-tilled systems for 6 yr and found that weed dynamics were affected substantially by tillage systems. However, their respective efficiency declined with increasing density of weeds.

Tillage Systems and Weed Dynamics. Tillage systems interact with soil type, cropping system, and weed flora to affect weed dynamics and weed management (Table 1). Weed germination, stand

establishment, and subsequent growth are affected by the tillage processes (Clements et al. 1996). Changing weed flora under different tillage regimes calls for a change in management options. Weed infestation is a serious problem during initial years under conservation tillage, which causes a reduction in crop yield (Blackshaw et al. 2001). On the other hand, some weed species may be suppressed in conservation tillage systems. For instance, wheat (*Triticum aestivum* L.) planting in no-till conditions reduced the seedling emergence rate of littleseed canarygrass (*Phalaris minor* Retz.), when compared with conventional plowing and sowing (Franke et al. 2007).

Tillage systems may also affect weed seed bank persistence in different seasons, but literature on this event is not clear. Effects of tillage on weeds are very specific and may vary from species to species. Emergence of tropical crabgrass [*Digitaria bicornis* (Lam.) Roemer & J.A. Schultes ex Loud.], tumble pigweed (*Amaranthus albus* L.), giant foxtail (*Setaria faberi* Herrm.), and common ragweed (*Ambrosia artemisiifolia* L.) was suppressed by spring cultivation, whereas that of velvetleaf (*Abutilon theophrasti* Medik.) and black nightshade (*Solanum nigrum* L.) was unaffected (Myers et al. 2005). Similarly, tillage had different effects on the distribution of common lambsquarters (*Chenopodium album* L.) and yellow foxtail [*Setaria glauca* (L.) Beauv.] in different seasons (Myers et al. 2005). Chauhan et al. (2006) also reported that weeds respond differently under different tillage regimes. For instance, intensive tillage may affect small-seeded weeds like squirreltail fescue [*Vulpia bromoides* (L.) S.F. Gray] through deep burial. Different tillage systems may have their own advantages and disadvantages in this regard but site-specific selection may facilitate weed management.

Strip Tillage to Target Weeds. No-till is a pragmatic option for resource conservation in many regions of the world but one serious concern in this system is poor crop establishment. Strip tillage is one such innovative approach focusing on targeted tillage for crop sowing while the remaining portion is untilled. This system improves soil quality, crop yield, and resource-use efficiency compared with a conventional tillage system, but weed management is a major issue hindering its adoption (Brainard et al. 2012). Weed dynamics are very complex under this system since the untilled zone may offer refuge to different predators and may utilize less mineralized nitrogen (N). In this way,

the situation and distribution of weeds are highly variable (Tarkalson et al. 2012). The tilled zone has well-incorporated residues, fertilizer, mineralized N, and higher temperatures, which contrast with the adjacent untilled patch. Such diversified conditions through targeted tillage directly alter weed dynamics as propagule movement and belowground biological functions are affected (Haramoto and Brainard 2012).

Winter annual weeds like common chickweed [*Stellaria media* (L.) Vill.] and henbit (*Lamium amplexicaule* L.) were more prevalent in the strip tillage system when compared with the conventional tillage (Brainard et al. 2012). This may be due to high survival and reproduction in the untilled portion. According to Brainard et al. (2013), perennials like horsenettle (*Solanum carolinense* L.) have the ability to recolonize quickly and are more problematic under strip tillage. Stable perennials like dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers) do not usually present this problem. Overall, annual, biennial, and perennial weeds have a different growth and emergence pattern under strip tillage (Brainard et al. 2012).

Weed Control through Tillage Rotation. Rotation of tillage intensity (number of operations) is a modern approach for weed management, especially under multiple cropping systems. In an experiment spanning 6 yr, it was observed that the density of summer annual weeds was reduced significantly when zero-tilled direct seeding was replaced with full-width tillage (Peachey et al. 2006). Another potential strategy is by adjusting crop rotations in such a way that the planting geometry automatically rotates the tillage patterns. For example, in the Pacific Northwest, vegetables on wider beds are rotated with cereals on narrow ridges (Brainard et al. 2013). In another study, foxtail barley (*Hordeum jubatum* L.) was effectively controlled through shifting from no-till to primary tillage with moldboard plow followed by disking in spring wheat (Donald 1990). Timing of tillage is another important factor affecting weed management.

Tillage affects weed dynamics, depending on seasonal variations, weed species, and type of tillage implement. There are numerous other factors, though, that are interacting and making such assumptions less solid and therefore more complicated.

Crop Nutrient Management

The role of nutrient management through fertilizer application in crop production is substantial

Table 1. Dominant weed species under different tillage systems.[a]

Tillage system	Description	Weed species	References
Conventional tillage	Plowing with moldboard plow	Common milkweed (*Asclepias syriaca* L.), yellow nutsedge (*Cyperus esculentus* L.), barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], quackgrass [*Elytrigia repens* (L.) Desv. ex B.D. Jackson], ladysthumb (*Polygonum persicaria* L.), wild mustard (*Sinapis arvensis* L.), dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers)	Clements et al. (1996)
		Bermudagrass [*Cynodon dactylon* (L.) Pers.] Field pennycress (*Thlaspi arvense* L.) Toothed dock (*Rumex dentatus* L.)	Samarajeewa et al. (2006) Bhattacharyya et al. (2009) Gill and Arshad (1995) Chhokar et al. (2007)
Deep tillage	Plowing with chisel plow	Redroot pigweed (*Amaranthus retroflexus* L.), yellow nutsedge, Canada thistle [*Cirsium arvense* (L.) Scop.], quackgrass, fall panicum (*Panicum dichotomiflorum* Michx.), sulfur cinquefoil (*Potentilla recta* L.), green foxtail [*Setaria viridis* (L.) Beauv.]	Clements et al. (1996)
Ridge tillage	Crops are sown on ridges made by ridger	Common milkweed, yellow nutsedge, wild carrot (*Daucus carota* L.), quackgrass, annual fleabane [*Erigeron annuus* (L.) Pers.], little burclover (*Medicago lupulina* L.), yellow woodsorrel (*Oxalis stricta* L.), ladysthumb, European red raspberry (*Rubus idaeus* L.), wild mustard, dandelion	Clements et al. (1996)
Minimum tillage Reduced tillage	Less preparatory tillage	Barnyardgrass, eclipta Wild oat (*Avena fatua* L.), prostrate knotweed (*Polygonum aviculare* L.)	Samarajeewa et al. (2006) Ozpinar (2006)
Zero tillage	Only localized soil disturbance at the time of sowing	Littleseed canarygrass (*Phalaris minor* Retz.), Japanese knotweed (*Polygonum convolvulus* L.)	Gill and Arshad (1995)
No-till	No or very minor soil disturbance	Velvetleaf (*Abutilon theophrasti* Medik.), common milkweed, Canada thistle, orchardgrass (*Dactylis glomerata* L.), wild carrot, quackgrass, little burclover, yellow woodsorrel, Virginia-creeper [*Parthenocissus quinquefolia* (L.) Planch.], clammy groundcherry (*Physalis heterophylla* Nees), yellow foxtail [*Setaria glauca* (L.) Beauv.], annual sowthistle (*Sonchus oleraceus* L.)	Clements et al. (1996)

[a] Studies mentioned in the table were conducted to evaluate the effect of tillage systems on weed dynamics. The dominant weed species were indicated on the basis of relative weed density.

and very clear. Weeds take up significant amounts of nutrients, just like crops. But the comparative effects on weed growth, population, distribution, and proliferation are generally ignored. Significant research in this area has shown that there exists a strong relationship between nutrient management and weed behavior and management. In a recent review, Bajwa et al. (2014) concluded that fertilizers affect weed growth, development, distribution, dynamics, persistence, emergence, and competitiveness.

Proper crop nutrient management can play a pivotal role in weed management. Different weeds show a variable response to nutrient management. For instance, dynamics of Persian darnel (*Lolium persicum* Boiss. & Hohen. ex Boiss.), wild oat (*Avena fatua* L.), and spineless Russian thistle (*Salsola collina* Benth.) were not affected by N fertilization, whereas redroot pigweed (*Amaranthus retroflexus* L.) was significantly affected (Blackshaw and Brandt 2008). The possible interactions might be due to the effect of fertilizer on weed–crop competition (Evans et al. 2003). Nutrient availability may alter the weed–crop competition duration. In a study, the application of N fertilizer changed the emergence pattern, density, and competitive ability of different weeds (Sweeney et al. 2008). N uptake and assimilation rates were reported to be quite higher in redroot pigweed and common lambsquarters as compared with the crop plants, making them more competitive and successful (Lindsey et al. 2013). Increased supply of nutrients over a period of time may reduce weed density but increase total weed biomass (Mohammaddoust-e-Chamanadad et al. 2006). Variable weed responses to fertility suggest that weeds can be controlled through regulating fertilizer management (DiTomaso 1995). Varying fertilizer doses, application timings, and methods can modify weed–crop competition (Blackshaw et al. 2004; Cathcart and Swanton 2003; Mesbah and Miller 1999).

The nature of fertilizers may affect weed biology and ecology. The rate of a particular fertilizer may also improve or suppress the emergence and persistence of a particular weed (Cathcart and Swanton 2003). Yin et al. (2005) reported that the percent abundance of shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.], Japanese bindweed (*Calystegia hederacea* Wallich), fixweed [*Descurainia sophia* (L.) Webb. ex Prantl], catchweed bedstraw (*Galium aparine* L.), swamp smartweed [*Polygonum amphibium* (L.) var. *emersum* Michx.], cone catchfly (*Silene conoidea* L.), and bird vetch (*Vicia cracca* L.)

was highly variable because of variation in the N–P–K source (inorganic and organic). Palmer amaranth (*Amaranthus palmeri* S. Wats.) was reported to be highly responsive to the increased fertilization rate (Ruf-Pachta et al. 2013). Toler et al. (2004) observed that normally weeds respond positively to the starter fertilizer dose and grow well. It is suggested that a specific amount of fertilizer can provide better crop growth but an over- or underapplication may facilitate the competing weeds, resulting in yield losses (Major et al. 2005). Shifting the N application from the spring season to the fall season reduced the density and biomass of four noxious weeds, including wild oat, green foxtail [*Setaria viridis* (L.) Beauv.], wild mustard (*Sinapis arvensis* L.), and common lambsquarters (Blackshaw et al. 2004). Therefore, proper consideration must be given to fertilizer type, dose, and application timing when devising weed management strategies.

Above all, the role of nutrient placement in weed management is crucial. Most of the weed seeds are present near the soil surface and fertilizer application in that zone may promote their emergence and subsequent growth as well (Guza et al. 2008). Blackshaw et al. (2004) reported up to 68% weed reduction in cases where N was injected rather than broadcast. Surface banding of N and P reduced weed pressure because of less availability to weeds as compared with broadcasting (Blackshaw 2005). Significant reductions in the shoot biomass of wild oat and green foxtail were observed when N fertilizer was applied through banding and injection rather than broadcasting (Blackshaw et al. 2004). Recently, Chauhan and Abugho (2013) reported a significant reduction in weed biomass by the subsurface fertilizer application in dry direct-seeded rice (*Oryza sativa* L.).

Better management of crop nutrition can improve weed management. Fertilizer type, dose, timing, and application method must be selected to best manage weed populations given their link.

Weed Seed Destruction

Most of the annual weeds produce a majority of seeds after completing their vegetative growth. Many seeds are retained in the soil seed bank, which creates problems after emergence in standing crops. Weed populations can be decreased by removing their seeds at maturity (Walsh et al. 2013). This strategy eliminates potential seeds from the system that can be deposited in soil or may germinate in coming seasons.

Table 2. Efficiency and adoption of harvest weed seed control systems in Australia.[a]

System	Weed species	Seed control (%)	Adoption	Extra benefit	Reference
Harrington seed destructor	Annual ryegrass	95	High adoption rate due to high efficiency	Residue retention for soil protection and fertility enhancement	Walsh et al. (2012)
	Brome grass	99			
	Wild oat	99			
	Wild radish	93			
Chaff carts	Annual ryegrass	73 to 86	Less due to problems of subsequent handling of chaff	Alternative use of chaff as feed for the livestock	Walsh and Powels (2007)
	Wild radish	95			
	Wild oat	74			Shirtliffe and Entz (2005)
Narrow windrow burning	Annual ryegrass and wild radish	99 for each	Most widely adopted as economical, simple, and efficient	Relatively ecofriendly as it avoids burning of the whole field	Walsh and Newman (2007)
Bale direct	Annual ryegrass	95	Less due to lack of availability of markets for baled material	Baled feed stock for livestock	Walsh and Powels (2007)

Harvest Weed Seed Control. The harvesting time of grain crops is very important as weed seeds are retained by plants and easy to remove and discard (Walsh and Powles 2007). Weed seeds can be collected and destroyed during or soon after harvesting of a crop. Harvest weed seed control has been developed in Australia and has shown promising results. This strategy can be implemented with the Harrington seed destructor (HSD), chaff carts, narrow windrow burning, and bale direct (Walsh et al. 2013). Each technology is based on the principle of weed-seed collection during grain crop harvest and seed destruction to avoid the replenishment of the seed bank.

Harrington Seed Destructor. Weed seeds present in annual grain crops remained a major concern for growers. A progressive grain producer, Ray Harrington, from Australia tested a cage mill for seed destruction in 2005 (Walsh et al. 2013). Cage mills are normally used to crush stone materials. Further research enabled scientists to destroy up to 90% of seeds of annual ryegrass (*Lolium rigidum* Gaudin) contained by wheat chaff during harvesting (Walsh et al. 2012). HSD is a modified cage mill having a chaff-and-straw transfer system along with power source. According to Walsh et al. (2012), field studies showed that HSD offers an impressive destruction rate of above 95% for annual ryegrass, ripgut brome (*Bromus diandrus* Roth), wild radish (*Raphanus raphsnistrum* L.), and wild oat seeds (Table 2). With such impressive results, HSD is a pragmatic option for the destruction of weed seeds.

Chaff Carts. Weed seeds that remain intact during conventional harvesting operations that are then added to the crop residues become randomly distributed to the whole field. To avoid this problem, chaff carts were introduced. Chaff carts are simply a cart on a trailer that is attached to a harvester that collects the chaff and places weed seeds in a specified bin (Walsh et al. 2013). Chaff carts effectively collect a significantly large amount of seeds of obnoxious weeds like annual ryegrass, wild oat, and wild radish (Shirtliffe and Entz 2005; Walsh and Powles 2007). Collected weed seeds and chaff are then dumped in piles to be burned.

Narrow Windrow Burning. This technique for controlling harvested weed seed is where chaff and residues containing weed seeds are concentrated in a narrow windrow during harvesting (Walsh et al. 2013). The harvester-mounted chute makes about a 60-cm windrow that is burned later, while keeping ecoprotection in mind (Walsh and Newman 2007). The limited burning of the windrow avoids pollution hazards as the whole field is not burned. Windrow burning is promising as it offers maximum weed control after harvesting of wheat, canola (*Brassica napus* L.), and garden lupin (*Lupinus polyphyllus* Lindl.) (Table 2).

Bale Direct. This is another sophisticated method of harvest weed seed control, in which chaff and residues from the harvester are converted into bales by a mechanized baler attached to the harvester (Walsh et al. 2013). Despite its efficient and clean

function, the adoption rate is lower, which may be due to the marketing issue with bales. However, it offers remarkable weed seed destruction (Table 2).

Hence, weed seed control during crop harvest is an encouraging prospect in the field of weed management. It helps to reduce weed seed bank and to minimize the chances of weed infestations in subsequent seasons. The development of technology in this sector may enable the farming community to manage weeds efficiently.

Weed Seed Predation. Seed predation through granivorous insects and small mammals is a useful tactic for weed control. Seed predation may be pre- (seeds still attached with plant) or post- (seeds dispersed after maturity) dispersal. Insects, birds, and small mammals are the major postdispersal weed seed predators (Heggenstaller et al. 2006; Menalled et al. 2007). Most *Coleoptera* and *Hymenoptera* insects are involved in weed seed feeding. Several species of carabid beetles and field cricket have been observed as potential predators of redroot pigweed, velvetleaf, large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and giant foxtail seeds in North America (Carmona et al. 1999). Mice consumed up to 20% of seeds of barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] and common lambsquarters in no-till soybean [*Glycine max* (L.) Merr.] and corn (*Zea mays* L.) in Canada (Carmona et al. 1999). Feeding habits and preferences of the predators significantly affect weed seed destruction and concomitant weed emergence. White et al. (2007) observed feeding choice of three beetle species (*Amara aenea, Anisodactylus sanctaecrucis*, and *Harpalus pensylvanicus*) and the field cricket (*Gryllus pennsylvanicus*). The beetles consumed more seeds of redroot pigweed than of giant foxtail.

Experimental and modeling studies have clearly shown that predation significantly affects weed seed demographics (Mauchline et al. 2005). A recent study in the Philippines reported a seed removal rate of 78 to 91% for junglerice [*Echinochloa colona* (L.) Link], goosegrass [*Eleusine indica* (L.) Gaertn.], and southern crabgrass [*Digitaria ciliaris* (Retz.) Koel.] over a 14-d period (Chauhan et al. 2010). Meiss et al. (2010) reported that the vegetative cover influences weed-seed predators by altering the habitat quality. Effective predation can be achieved by delaying tillage or increasing interval between land preparation and seeding (Chauhan 2012; Chauhan et al. 2010). Seed predation is a potential nonchemical weed management option. It can be

used alone or in combinations with other cultural management practices.

Allelopathy

A large proportion of the existing allelopathy research findings is focused on its role in weed management. Researchers have observed that allelopathy is a great organic weed management tool (Cheema et al. 2004; Iqbal et al. 2007; Jamil et al. 2009). Allelochemicals suppress physiological functioning of plants and thus retard growth when applied at high concentrations. This phytotoxic activity of allelochemicals is responsible for growth suppression of weeds (Farooq et al. 2013). Allelopathy can be expressed in two major ways for weed management: cultural means and allelopathic extracts application.

Cultural Means. Allelopathic sources can be introduced through crop rotations. Allelopathic crops are included in a planned rotation where their residual effects may suppress weed flora and provide a weed-free environment to the next crop. Mulches based on allelopathic residues are good means of weed control (Cheema et al. 2013). Emerging weed seedlings are effectively controlled by allelopathic mulches through the leaching of allelochemicals; however, established weed flora is difficult to eradicate through this method (Farooq et al. 2013). Similarly, incorporation of sorghum [*Sorghum bicolor* (L.) Moench ssp. Bicolor] vegetative parts significantly reduced weed density in wheat fields (Cheema and Khaliq 2000). Soil incorporation of sorghum residues alone and when mixed with sunflower (*Helianthus annuus* L.), rice, and *Brassica* spp. trashes provided effective control against littleseed canarygrass, common lambsquarters, toothed dock (*Rumex dentatus* L.), and horse purslane (*Trianthema portulacastrum* L.) in wheat, cotton (*Gossypium hirsutum* L.), and corn fields (Table 3). Surface mulching of sorghum, brassica, and cone marigold (*Tagetes minuta*) controlled weeds in rice, cotton, and mung bean [*Vigna radiata* (L.) R. Wilczek] (Batish et al. 2007; Khaliq et al. 2010; Sadia et al. 2013). Intercropping is another prospect for weed management through allelopathy (Table 3). Allelopathic crops can also be introduced as cover and smother crops. Allelopathic crops like rye (*Secale cereal* L.), velvet bean [*Mucuna pruriens* (L.) DC.], and barley (*Hordeum vulgare* L.) offered effective control against southern crabgrass, barnyardgrass, common purslane, and *Amaranthus*

Table 3. Cultural weed management through allelopathic application.

Application method	Allelopathic source	Application rate	Weeds controlled	Reduction in weed biomass	Crops benefitted	Reference
		t ha^{-1}		%		
Soil incorporation	Sorghum	2 to 6	Littleseed canarygrass, common lambsquarters, fumitory (*Fumaria officinalis* L.) toothed dock	26 to 56	Wheat	Cheema and Khaliq (2000)
	Combinations of sorghum, rice, and sunflower	5 to 7.5	Horse purslane, purple nutsedge	60 to 98	Wheat, corn, cotton	Khaliq et al. (2010)
Surface mulch	Sorghum	3.5 to 10.5	Horse purslane, field bindweed (*Convolvulus arvensis* L.), bermudagrass, purple nutsedge	35 to 96	Cotton, mungbean	Khaliq et al. (2010)
	Black mustard (*Brassica nigra*)		Wild oat	68		Farooq et al. (2011)
	Cone marigold	1	Purple nutsedge, barnyardgrass	41	Rice	Batish et al. (2007)
Intercropping	Cotton + sorghum	—	Purple nutsedge	89 to 92	Cotton	Iqbal et al. (2007)
	Cotton + soybean			83 to 92	Cotton, soybean	
	Cotton + sesame (*Sesamum indicum*)			80 to 87	Cotton, sesame	
	Wheat + chickpea (*Cicer arietinum*)	—	Wild oat, scarlet pimpernel (*Anagallis arvensis* L.), purple nutsedge, barnyardgrass, lesser swinecress [*Coronopus didymus* (L.) Sm.]	/	Wheat, chickpea	Banik et al. (2006)
Cover crops	Rye	—	Common purslane (*Portulaca oleracea* L.), *Amaranthus* spp.	/		Nagabhushana et al. (2001)
	Velvet bean	—	Barnyardgrass	/		Peters et al. (2003)
	Barley	—	Southern crabgrass, barnyardgrass	/	Soybean	Farooq et al. (2011)
Smothering crops in rotation	Oat (*Avena sativa*), pearl millet (*Pennisetum glaucum*), Egyptian clover (*Trifolium alexandrinum*)	—	Purple nutsedge, barnyardgrass	/	Rice grown after wheat	Kobayashi et al. (2004)
	Wheat	—	Small bromerape (*Orobanche minor* Sm.)	/	Red clover (*Trifolium pretense*)	Lins et al. (2006)

—, not applicable; /, not recorded

spp. in different crops (Farooq et al. 2011). Cultural means of allelopathic application have varying degree of success, depending upon environmental and managerial factors.

Allelopathic Extracts. Allelochemicals are secondary metabolites with complete solubility in water. This feature enables them to be extracted in water after soaking herbage and subsequently used as foliar spray. Crop water extracts have been used successfully for weed suppression through foliar application in different crops (Bajwa 2014). Sorghum water extract is one of the most widely used natural herbicides. Concentrated sorgaab (sorghum water extract) controlled common lambsquarters, littleseed canarygrass, and toothed dock in wheat crop (Cheema and Khaliq 2000). Similarly, it offered a substantial reduction in weed density and weed biomass in rice, cotton, corn, and mungbean (Table 4). Combined use of different crop water extracts improves weed management through synergistic effects (Table 4). In a laboratory experiment, Bajwa et al. (2013) showed that single and combined applications of water extracts of some tree plants and weeds suppressed the germination and growth of wild oat. Integrating the use of half doses of recommended chemical herbicides and different crop water extracts together offered favorable weed control (Jabran et al. 2010; Rehman et al. 2010).

Improving Allelopathic Potential of Crops. Improvement in the allelopathic potential of crops to offer a substantial competitive advantage against resistant weeds is under way. Keeping in view the genetic variability existing in cereals, crops have been bred to improve their allelopathic potential (Worthington and Reberg-Horton 2013). Modified lines of birdsrape mustard (*Brassica campestris* L.) have been developed to increase their allelopathic expression, which offered successful weed control in corn and soybean (Haan et al. 1994). Highly weed-suppressive rice genotypes (e.g., hybrid of Kouketsumochi and IR24) have been developed through conventional breeding, which suppress noxious weeds like junglerice and red rice (*Oryza sativa* L.) to a great extent. Such cultivars are commercially available in China and the United States (Fragasso et al. 2013). Improvement in the allelopathic potential of crops through genetic engineering is among the latest trends in the field of agrobiotechnology (Nawaz et al. 2014). Despite the complex genomics, it is feasible to identify the distinguished genes involved in such mechanisms (Singh et al.

2003). Wu et al. (2000) screened a large pool of winter wheat accessions (over 400) to assort allelopathic active genes. With the help of genetic tools, genes have been located that are responsible for the production of allelochemicals. Location of such genes on chromosomes and quantitative trait loci (QTLs) are also being assessed (Jensen et al. 2008). Gene mapping for hydroxamic acid expression in wheat has been analyzed and QTLs are being used for gene transfer (Wu et al. 2000, 2003). Crops with superior allelopathic profile and suppressive ability will improve weed management in coming days.

Herbicide-Tolerant (HT) Crops

An increasing trend of genetic modifications in crops has been observed during the last 2 decades. Major transgenic traits introduced in crops are herbicide resistance, insect resistance, virus resistance, and stress resistance. However, HT crops comprise the vast majority (83%) of genetically modified (GM) crops (Beckie et al. 2006). The reason behind the introduction of HT crops and their rising acceptance is primarily due to the effective weed control. Biotechnology has provided successful HT crops that are tolerant to glyphosate, glufosinate, bromoxynil, imidazolinone, and dicamba (Gealy et al. 2003; Givens et al. 2009). HT crops like cotton, corn, canola, rice, sugar beet (*Beta vulgaris* L.), alfalfa (*Medicago sativa* L.), brassica, and soybean (Gealy et al. 2003) have revolutionized weed management in the United States (Givens et al. 2009), Canada (Beckie et al. 2006), Australia (Duke and Powles 2009) and many other countries.

A majority of HT crops, including soybean, cotton, corn and canola, is glyphosate resistant (GR) (Green 2012). GR crops have the largest share in transgenic HT crops globally. GR cotton was also adopted quickly in the United States and other countries because of convenience and effective weed management. Singh (2014) reported that > 95% of cotton varieties planted in the United States were GM varieties where area under stacked gene cotton varieties increased from 24% (2000) to 77% in 2014. Weed management in the conventional non-HT cotton was difficult because of the narrow spectrum and ineffectiveness of PRE herbicides (Duke and Powles 2009). GR canola has been successful in different parts of world. However, about 90% of the global GR canola production is in Canada (Gianessi 2005). HT soybean is the most

Table 4. Weed management through allelopathic crop water extracts alone and in combination with other extracts and reduced doses of herbicides.[a]

Allelopathic extract/ combination	Weeds controlled	Percentage reduction		Crops benefited	Reference
		Weed density	Weed biomass		
Sorghum	Fumitory, littleseed canarygrass, toothed dock, common lambsquarters	22 to 44	35 to 49	Wheat	Cheema and Khaliq (2000)
	Horse purslane, bermudagrass, purple nutsedge	47	29 to 40	Cotton	Cheema et al. (2002)
	Purple nutsedge, common lambsquarters, fieldbind weed	18 to 32	24 to 60	Mungbean	Cheema et al. (2001)
	Junglerice, purple nutsedge, rice flatsedge (*Cyperus iria* L.)	–[c]	40	Rice	Wazir et al. (2011)
Sunflower	Wild oat, yellow sweetclover [*Melilotus officinalis* (L.) Lam.], broadleaf dock (*Rumex obtusifolius* L.)	11 to 34	2 to 16	Wheat	Naseem et al. (2010)
Sorghum + sunflower Sorghum + brassica Sorghum + tobacco (*Nicotiana tabacum*) Sorghum + sesame	Wild oat, littleseed canarygrass	–	10 to 62	Wheat	Jamil et al. (2009)
(Sorghum)[b] + isoproturon (Sorghum + sunflower) + pendimethalin	Littleseed canarygrass Common lambsquarters	94 84	65 67	Wheat Sunflower	Cheema et al. (2002) Awan et al. (2009)
(Sorghum) + pendimethalin	Horse purslane	52	50	Cotton	Iqbal et al. (2009)
(Sorghum + brassica) + pendimethalin	Horse purslane, bermudagrass, purple nutsedge, lesser swinecress	43 to 91	37 to 94	Canola	Jabran et al. (2010)
(Sorghum + sunflower + rice) + butachlor	Barnyardgrass, rice flatsedge, crowfootgrass [*Dactyloctenium aegyptium* (L.) Willd.]	67 to 74	66 to 76	Rice	Rehman et al. (2010)

[a] All the extracts were applied two to three times in a pure form without dilution and herbicide doses were reduced to half.
[b] Allelopathic extracts used in combination with reduced dose of herbicide are presented in parentheses.
[c] –, not recorded.

prevalent, where around 60% of the total production is transgenic crops (Beckie et al. 2006).

Nontransgenic HT corn, canola, wheat, soybean, sunflower, and sorghum developed in the past were tolerant to imidazolinones, photosystem II inhibitors, and sulfonylureases (Green 2012). Clearfield (CF) rice is exclusively nontransgenic, developed through the breeding technique, relying totally on rice DNA. CF rice is resistant against imidazolinone herbicide, which is very effective against red/weedy rice. Weed control in CF rice is very easy as it allows PRE and POST application of imazethapyr (Azmi et al. 2012). Wheat is the crop in which biotechnology has not given successful commercial varieties yet. A lot of work is under progress at Monsanto, Bayer, BASF, and many other multinational companies for biotechnological development in wheat. Research trials have shown that Roundup Ready wheat is safe, nutritious, and efficient in terms of weed management (Obert et al. 2004). However, its commercialization has not taken place.

Critics of HT crops raise concerns about environmental hazards, health issues, biodiversity decline, and moral obligations. Above all, the conundrum of herbicide resistance development in weeds has seriously threatened the sustainable use of HT crops as a weed management option (Heap 2014). No doubt, HT crops are playing a remarkable role in weed management but a serious problem remains the leakage of resistant genetic traits from crops to the associated weeds (Owen and Zelaya 2005). To allay the problem of herbicide resistance in weeds, a second-generation phase of HT crops is being developed (Mortensen et al. 2012). In the future, integrated approaches on the basis of stacked gene crops and rotational use of herbicides may offer effective weed control in different cropping regimes.

Bioherbicides

Bioherbicides are potential plant pathogens applied to agroecosystems exogenously and repeatedly to control weeds. Biological weed control gained traction in the mid-80s when some of the potent pathogens were successfully utilized to make effective formulations for weed control. Despite its early gains, this particular field is still struggling regarding inventions or launching products, but consistent theoretical development is still evident (Hallett 2005). Given the changing climate, evolution of herbicide resistance in weeds, and lagging science of synthetic herbicides, innovations in the field of bioherbicides are much needed (Charudattan and Dinoor 2000). Currently, eight bioherbicides have been registered and are being commercialized. These products have been proven effective in specific weed management scenarios and helped a great deal in effective integrated weed management. Most of them include fungal pathogens and are based in the United States or Canada. Over 200 plant pathogens have been identified for use of this purpose after considerable technological developments (Hoagland 1996). Biotechnology has a pivotal role in the development and modification of bioherbicides. Advancements in screening, formulation, augmentation, and application of bioherbicides depend upon biotechnological tools (Ghosheh 2005).

Bioherbicides have some unique advantages, making them suitable for weed management in a variety of environments. One of the most important benefits of bioherbicides is their specific action. There are no side effects like residual toxicity, nontarget destruction, or health issues (Charudattan and Dinoor 2000). However, the role of bioherbicides in modern weed management is complementary rather than exclusive. They lack attributes to be considered as a solo scavenger (Hoagland et al. 2007). There are many limitations and constraints in the implementation of bioherbicides in weed management (Table 5). Comprehensive research on genetic, biological, environmental, technological, and financial aspects of this technology is recommended.

Thermal Weed Management

Plant tissues are susceptible to high temperatures, when most of the physiological functions are disrupted because of membrane rupture, protein denaturation, and enzyme inactivation. This led to the development of weed management strategies involving high temperature. Most of the plants die after exposure temperatures between 45 and 55 C (Zimdahl 2013). To control weeds, heat may be used in different ways, including direct flaming, solarization, and microwave technology.

Flaming. Flaming is a unique technique to kill weeds through the use of direct heat in the form of fire. The temperature of about 55 C is used to kill the weeds by destroying the cell wall structure. Fuel and temperature requirements depend on weed growth stage and biomass. However, for effective weed control, frequent flaming is often needed (Ascard 1994). Commonly, propane is used as fuel,

Table 5. Limitations in bioherbicide development.

Type	Limitations Factors	Processes affected	Suggested measures	Reference
Environmental	Effect of temperature, dew period, relative humidity, rainfall; environment of phyllosphere	Formulation and efficacy	Frequent applications, improvement in formulation process, use of vigorous pathogens, improved application technology	Charudattan and Dinoor (2000); Ghosheh (2005); Hallett (2005); Scheepens et al. (2001)
Biological	Host specificity, resistance, infection period, and narrow spectrum	Formulation, infection, effectiveness, augmentation	Genetic improvement, stacking technology to widen the effectiveness spectrum, integration with chemical herbicides	Auld and Morin (1995); Charudattan (2001, 2005)
Technological	Pathogen strain identification, shelf life, application techniques	Formulation, application	New formulations, use of surfactants and adjuvants to improve application and efficacy	Ghosheh (2005); Patzoldt et al. (2001)
Legal	Rigid registration laws, dominating chemical herbicide industry	Registration, dissemination	Restructuring registration laws and extension policies	Ghosheh (2005)
Financial	Funding for research programs, commercialization	Overall development and progress of bioherbicides	Allocation of funds for integrated programs based on bioherbicide development, development of cross-disciplinary projects	Ghosheh (2005); Hallett (2005); McConnachie et al. (2003)

but relatively renewable alternatives like hydrogen are also under consideration (Andersen 1997). Flame weeding is most prevalent in European countries (Bond and Grundy 2001). Weeds that have thin leaves like common lambsquarters, nettle, and chickweed are readily burnt through flaming, whereas shepherd's purse, barnyardgrass, and annual bluegrass (*Poa annua* L.) could not be burnt in a single operation (Ascard 1995). Flaming has shown good results after weed emergence but before crop emergence in potato (*Solanum tuberosum* L.), sugar beet, carrot (*Daucus carota* L.), and cayenne pepper (*Capsicum annuum* L.) (Melander 1998). Rask et al. (2012) studied the effect of flaming on grasses and shared some positive results regarding the control of grasses. Knežević and Ulloa (2007) evaluated broadcast flaming in different agronomic crops to manage barnyardgrass, green foxtail, velvetleaf, and redroot pigweed and concluded that flaming offers best control for broad-leaved weeds, whereas the grasses are less susceptible. Corn and sorghum (both from the Poaceae family) were tolerant to flaming, whereas soybean and sunflower were susceptible (Knežević and Ulloa 2007). Weeds of corn were significantly controlled through integration of tillage and flaming (Knežević et al. 2011).

Flaming has provided effective weed control in different ecosystems and has led to system stability.

In many regions, fire is not a threat but a tool to reduce competition and to improve nutrient cycling (Kyser and DiTomaso 2002). A quick response and prompt results are also the distinct features of flame weeding. With advancement in this subject, logistic models have been developed to estimate the efficiency of flame weeding and species response to flaming (Ascard 1995). Further research is needed to optimize the technology for its safe use in field crops.

Solarization. Solarization is a practice of covering the soil with plastic sheets, converting solar energy to heat to kill weeds before sowing of the crop. Soil sterilization is an effective approach toward weed management by applying steam directly to kill weeds or by solarization. It suppresses weed germination and kills existing seedlings (Horowitz et al. 1983). Additional benefits of solarization are improved crop germination due to optimal temperature attainment and destruction of plant pathogens due to the sterilization effect of heat. Winter annual weeds were found to be more sensitive to solarization, but summer annuals like crabgrass and common purslane were less affected by heat. Perennials like bermudagrass (*Cynodon dactylon* L.), Johnsongrass [*Sorghum helepense* (L.) Pers.], and field bindweed (*Convolvulus arvensis* L.)

were least affected by solarization because of their well-developed underground parts (Horowitz et al.1983; DeVay et al. 1991). Solarization duration and its interaction with cultivated soil depth cause significant difference in weed control. It works more efficiently in tilled soils. Solarization along with green manuring suppressed annual bluegrass significantly (Peachey et al. 2001). Integrated use of polyethylene sheets and poultry manure mulch affected emergence of field dodder (*Cuscuta campestris* Yuncker) (Haidar and Sidahmed 2000). Solarization for 2 mo with polyethylene covering killed 95% of broomrape (*Orobanche ramosa* L.) seeds (Mauromicale et al. 2005). The success of solarization depends upon exposure to light, soil texture, moisture status, and weed flora. It is a pragmatic option and has vast implications for integrated weed management.

Microwaves and Radiations. Use of microwave energy to kill weeds has gained popularity in the recent past. It is based on the high energy of microwaves, which can kill weeds very efficiently. This method is highly targeted and there is no fear of nontargeted damage (Rask and Kristofferson 2007). Microwaves were successfully used in Denmark for the control of little mallow (*Malva parviflora* L.), hairy fleabane [*Conyza bonariensis* (L.) Cronq.], and gooseberry gourd (*Cucumis myriocarpus* E. Mey. ex Naud.) (Brodie et al. 2007). This technology is effective against many weeds, but the energy required is very high, which increases its cost (Sartorato et al. 2006). However, its efficiency and energy budget may be decreased by flux configuration and through induction of thermal runaway in weed plants, making it comparable with other weed-control tools in terms of cost (Brodie et al. 2011). Similarly, laser radiation may be used effectively to kill weeds (Rask and Kristofferson 2007). In the United States, laser beams were used to kill water hyacinth plants. Lasers transfer high energy to plant tissues and raise the water temperature at the cellular level, resulting in cell death. Mathiassen et al. (2006) studied the biological efficacy of laser treatment against common chickweed and scentless chamomile [*Tripleurospermum inodorum* (L.) Schultz-Bip.] under varying levels of exposure time and observed that weeds were significantly suppressed. Use of ultraviolet radiation for weed management has also been tested (Andreasen et al. 1999; Day et al. 1993) and it was observed that the ultraviolet energy acts severely on plant tissues. It kills weeds just like flaming; however, limited development of this technology is due to possible health hazards. Further research is needed in this particular aspect to develop economically viable options on a sustainable basis.

Hot Water, Steam, and Hot Air. Heat can also be used to kill weeds through hot water application. Hot water treatment for weed control has been trialed in many countries with a great deal of success (Rask and Kristofferson 2007). In the 1990s, a commercial tool, Aqua Heat, was developed in the United States to apply hot water for weed control (Berling 1992). Hot water application proved effective against most of the annual and a large number of perennial weeds. The effects were even comparable against a glyphosate application. Similar kinds of equipment were successfully used against weeds in New Zealand, where hot water remained in contact with weeds for a longer period of time (Rask and Kristofferson 2007). Hot water equipment for weed control is also available in Denmark and the Netherlands. Hot water treatment is safe and has no side effects like flame weeding or radiation methods. Its effectiveness is greater under dense weed population because of increased penetration ability (Hansson and Ascard 2002). Because of a greater success rate, this technique is being considered in precision weed management strategies in European countries. Use of steam instead of hot water has been observed as a more effective, quick, and sustainable method, especially in cases where weed control is on relatively hard surfaces (Rask and Kristofferson 2007). Engineering efforts are needed in this area to improve the efficiency of availability of equipment and to introduce new equipment for weed management in crop production regimes.

Electrocution. The practice of weed control via electric shock is called electrocution. Although it is a less-researched domain, evidence supports the fact that weeds can be killed by spark discharge or electrical contact (Diprose and Benson 1984; Parish 1990). The strength of electric shock, contact or exposure duration, weed species, morphological features, and growth stage significantly affect the success of electrocution. The severity of damage is aggravated in cases of dry soil conditions (Diprose and Benson 1984). However, because of higher costs involved, energy crises, and hazards to operators, its application in agriculture is limited. In the future, this particular method may have practical implications, especially in organic farming.

Precision Weed Management

Precision weed management is based on bringing in information technology for decision making about site-specific weed control (Christensen et al. 2009). Spatial heterogeneity in weed infestation provides the basis for the implication of such systems. For instance, early-season site-specific weed management is the approach of weed patch detection, mapping, and prompt control through machine vision, while keeping the economic feasibility in mind (Freckleton and Stephens 2009).

Modeling. Modeling is a potential tool to assess the actual scenario of weed dynamics for the subsequent management strategies. Weed modeling is a relatively complex subject and several mathematical and statistical tools are used to form a precise model (Freckleton and Stephens 2009). Successful modeling that is based on the data collected through sensing technologies provides a clear picture about weed seed bank dynamics, emergence patterns, replacement trends, competitiveness, canopy architecture, and possible yield losses (Christensen et al. 2009; Rew and Cousens 2001). Decision-making tools and models help to identify and measure the influence of variables like soil conditions, environmental factors, crop husbandry practices and mechanization on weed emergence, distribution, and competition patterns (Christensen et al. 2009).

There are generally two aspects of weed modeling: one is efficacy based and the other is population based (Freckleton and Stephens 2009). Efficacy-based modeling involves the assessment of control measures and their effectiveness (Wiles et al. 1996). It helps in making decisions about herbicide choice and dose for appropriate weed control. For instance, the weed model SELOMA helps to decide the suitable herbicide under prevailing conditions (Stigliani and Resina 1993). The precision of any model depends on details provided, number and nature of variables, and the validation process (Freckleton and Stephens 2009). On the other hand, population-based predictive models are intensively researched and are more prevalent in weed science. They are used to deliver information about weed infestation patterns, weed density, and weed cover in a given area over a period of time. Some of the most useful deterministic population models include HERB, WEEDSIM, GWM, PALEWEED, and GESTINF (Christensen et al. 2009; Freckleton and Stephens 2009).

The economic feasibility of a control measure can also be measured precisely through modeling where only cost-effective strategies may be considered (Christensen et al. 2009). Another beneficial aspect of weed modeling is the evaluation of weed–crop competition status (Christensen et al. 2003). The findings of a 5-yr study were encouraging, as the predictions about dose reduction, economic status, and competition intensity were precise (Christensen et al. 2009). Modeling for weed dynamics in wheat, sugar beet, corn, and barley also provided good results in terms of precision and decision support (Gerhards and Christensen 2003). The modeling approach is very impressive for the implementation of precision weed management; however, there are certain limitations with it. Most of the predictive decision support models rely on weed data that consider weed populations in even distributions and thus foresee the yield losses in an exaggerated manner. Similarly, the weed population trend may be misread sometimes, because of uneven weed distribution (Brain and Cousens 1990; Christensen et al. 2009). Problems related to input data, remote sensing, and choice of model may also influence the efficiency and precision of weed models. Fine tuning of the whole regime may improve the efficacy of modeling and consequently the implication of precision weed management.

Remote Sensing. Remote sensing is a modern technology used in agriculture to ensure the precision management of inputs as well as to frame out weed presence (Thorp and Tian 2004). Remote-sensing tools can be used to detect weed patches, or in other words, to map weed densities in field crops and forest areas. It is well known that weeds are mostly prevalent in patches on agricultural lands. Therefore, remote sensing is a good option to reduce the herbicide application and cost of production by enhancing the herbicide application efficiency (Medlin and Shaw 2000). Remote sensing is based on differential spectral reflectance of weeds and other vegetation, like crops and spectral resolution of the instrument in use. These two factors govern the efficacy of remote sensing in mapping weeds. It is a prerequisite that the pixel quality must be higher than the difference in reflective indices of vegetation. The higher this difference is and the sharper the pixels, the higher the quality of the picture will be, which is crucial for subsequent mapping (Zhang et al. 1998). On the other hand, stubbles or residues may hinder because of the similarity with emerging or even established

Table 6. Weed species mapped against different background environments through remote sensing.

Weed species mapped		Background environment	Reference
Name	Family		
Quackgrass	Poaceae	No-till corn at seedling stage having stubble and bare soil background	Lamb and Brown (2001)
Foxtail grasses (*Setaria* spp.)	Poaceae		
Dandelion	Asteraceae		
Common lambsquarters	Chenopodiaceae		
Wild oat	Poaceae	Seedlings of *Triticale* sown with clover	Lamb et al. (1999)
Hairy panic (*Panicum effusum*)	Poaceae	Canola stubbles	Lamb and Weedon (1998)
Wild radish (*Rhaphanus raphanistrum*)	Brassicaceae	Oat	Lamb et al. (1999)
Wild oat	Poaceae	Wheat	
London rocket (*Sisymbrium irio* L.)	Brassicaceae	Cabbage (*Brassica oleracea* var. *capitata*)	Menges et al. (1985)
Johnsongrass	Poaceae	Sorghum	
Pigweed	Amaranthaceae	Mature cotton	
Ragweed parthenium (*Parthenium hysterophorous* L.)	Asteraceae	Carrot	
Broom snakeweed [*Gutierrezia sarothrae* (Pursh) Britt. & Rusby]	Asteraceae	Rangelands	Everitt et al. (1987)
Spiny aster (*Aster spinosus* Benth.)	Asteraceae		
Meadow hawkweed (*Hieracium pratense* Tausch)	Asteraceae	Pastures	Lass and Callihan (1997)
Oxeye daisy (*Chrysanthemum leucanthemum* L.)	Asteraceae	Forest meadows	
Common cocklebur (*Xanthium strumarium* L.)	Asteraceae	Soybean	Hestir et al. (2008)
Perennial pepperweed (*Lepidium latifolium* L.)	Brassicaceae	Estuaries	Hestir et al. (2008)
Water hyacinth [*Eichhornia crassipes* (Mart.) Solms]	Pontederiaceae		
Brazilian waterweed (*Egeria densa* Planch.)	Hydrocharitaceae		

weed vegetation, which makes it hard to discriminate the living and nonliving vegetation. Similarly, at the earlier stages of the crop stand, this problem may be enhanced in part, but a simple solution is the comparison of images obtained with the maps of fallow land plots (Lamb and Weedon 1998).

Some weed species have been successfully mapped through remote sensing in cereal and legume crops, especially with higher-resolution imagery in row crops (Table 6). It was observed that weeds can be identified from visuals and can be discriminated from the background vegetation. The prime considerations about weed floristic composition, canopy architecture, and leaf dimensions have made it feasible to map them against different crops' background (Zhang et al. 1998). Differences in growth stages of weeds and crops, emergence patterns, growing habits, vigor, and characteristics at maturity also provide help in sensing them remotely to sketch fine and accurate maps (Lamb and Weedon 1998; Medlin and Shaw 2000). Some researchers use classification algorithms for POST weed sensing. These algorithms are actually based on statistical variability and the trend between the weed densities before crop emergence against bare soils and after expected populations (Lamb and Weedon 1998; Lass et al. 2005). In this way, remote sensing is currently being used for statistical modeling of weed distribution patterns (Lass et al. 2005). One such technique is geostatistics, which is used for descriptive analysis of weed aggregation and spatial variation (Medlin et al. 2000). Different methods of remote sensing are based on this principle; however, they differ in the position of

the sensor, resolution used, and mapping orientation. Each has merits and demerits associated with efficacy of tools being used (Table 7).

Aerial and Satellite Remote Sensing. Aerial installation of weed sensors is a useful way to monitor a large area. This technique can be used for imaging weed vegetation as it provides an overhead view of the whole field. The use of aerial sensors for weed detection was started after the 1980s and has gained reasonable popularity since then (Thorp and Tian 2004). Color imaging was the first method used in this technology and which later developed into color infrared photography to better screen weeds from remaining vegetation. Reflective indices of the near-infrared (NIR) spectrum were more variable as compared with those of visible spectrum (Price 1994). Noxious weeds of different arable crops were successfully detected and mapped with reasonable accuracy (Table 6). Spectral signature mixing in weed sensing through aerial sensing remains an issue and was only used for thematic classifications. Thus, weed infestation regions were delineated on the basis of statistical variability measurements. On the other hand, aerial tools are being successfully used to delineate weed boundaries in rangelands, as thematic classification is more appropriate in such systems (Medlin et al. 2000). However, computer-based weed sensing is still a useful option via aerial sensor data input. Airborne sensors are more flexible in their function and application.

Satellite images are used for weed sensing. It is very common to use global positioning systems (GPS) and geographic information systems (GIS) for spectral analysis, tracking, and aerial location detection—their role in weed detection, though, is rare and complex. Multispectral images are commercially available from different satellites (Stafford 2000). The IKONOS satellite offered 4-m resolution in a multispectral mode. Similarly, images from SPOT, AVHRR, and TM satellites are in the range of 30 m to 1.1 km. These multispectral images fall within a wide range of visible, infrared (IR), and NIR spectrums (Lamb and Brown 2001; Lamb and Weedon 1998). In a previous study, Memon et al. (2011) surveyed and mapped noxious weed species of wheat and cotton in the cotton–wheat cropping system through GIS and GPS. Recent advancement in the use of aerial and satellite weed sensing is replacing color and color infrared imaging with hyperspectral and multispectral technologies. Multiband multispectral cameras have been introduced to take images of densely populated weed species;

encouraging results have been observed (Hestir et al. 2008). The use of multispectral scanners is becoming popular in place of aerial or satellite imaging and video sensing. For instance, the compact airborne spectrographic imager is an airborne scanning device operated at a height of 1,200 m with great accuracy (Stafford 2000).

On-Ground Remote Sensing. To compensate for the problems associated with aerial and satellite remote sensing, ground-based sensing devices have been developed. On-ground remote sensing has a high degree of precision and efficiency. Photodetectors are actually used along with sensors. These give a very clear picture about weed infestation and density (Thorp and Tian 2004). On the basis of this principle, weed-detection model instruments have been developed. Hanks and Beck (1998) analyzed two commercially available systems, the Detectspray Model S-50 and the WeedSeeker Model PhD 1620, which use photoelectric sensor readings to trigger nozzles for a spraying application. Photoelectric sensors are not able to distinguish between crop and weeds; therefore, plastic spray hoods were used to prevent vegetation within the crop rows from triggering the spray (Thorp and Tian 2004).

Unmanned Aerial Vehicles (UAVs). Weed populations in patches make it difficult to assess the actual scenario from the remote images with very small pixels. Weeds growing against a soil or stubble background offer difficulty in gathering accurate information (López-Granados 2011; Torres-Sánchez et al. 2013). To address these issues, UAVs have been introduced in recent years. These are automated drones with fixed high-resolution cameras, able to fly at very low altitudes. Given their ability to fly immediately, frequent high-resolution imaging capabilities, capacity to capture images even under clouds, placement flexibility, and economic feasibility are the unique selling points of UAVs, which make viable tools for future automated weed management (Anderson and Gaston 2013; Peña et al. 2013; Torres-Sánchez et al. 2013 Xiang and Tian 2011). The use of UAVs in agriculture is still premature but encouraging. A UAV was used in monitoring glyphosate application to turf grasses through multispectral imaging (Xiang and Tian 2011). In another study, Primicerio et al. (2012) used a six-rotor UAV to sense vineyard growth through a multispectral camera. The use of acquisition, georeferencing, and mosaicking in UAV imaging has improved this

Table 7. Weed detection through different remote-sensing tools.

Remote-sensing method		Weeds detected and mapped	Advantage	Drawback	Reference
Tool/process	Type				
CC and CRI[a] photography	Aerial remote sensing	Common milkweed, ragweed parthenium, johnsongrass, London rocket, palmer amaranth, broom snakeweed, spiny aster	Superior image resolution	Mixing of spectral signatures for weeds and crop canopies, slow, complex	Everitt et al. (1987, 1992, 1993); Menges et al. (1985);
Video imaging endorsed by GPS and GIS	Aerial and satellite remote sensing	Blackbrush acacia (*Acacia rigidula* Benth), sweet acacia [*Acacia farnesiana* (L.) Willd.], woolly loco (*Astragalus mollissimus* Torr.), wooton loco (*Astragalu wootonii* Sheldon), yellow starthistle (*Centaurea solstitialis* L.), meadow hawkweed	Quick turnaround time, fast, higher computer compatibility	Low-quality pixels, lesser discrimination rate	Anderson et al. (1993); Everitt et al. (1993); Lass and Callihan (1997); Thorp and Tian (2004)
WeedSeeker photodetector	On-ground remote sensing	Meadow hawkweed	Versatile design, efficient, Precise	Problem with densely populated fields	Hanks and Beck (1998); Thorp and Tian (2004)
DetectSpray photodetector	On-ground remote sensing	Ragweed parthenium	Accurate, detected even small growing weeds in dense populations	Interference with solar radiation	Blackshaw et al. (1998)
Satellite imagery	Satellite remote sensing	Shinnery oak (*Quercus havardii* Rydb.), blackbrush acacia	Provision of high volume of processing data	Less operational flexibility regarding real-time monitoring	Anderson et al. (1993); Everitt et al. (1993)
Airborne sensors	Aerial remote sensing	Common St Johnswort (*Hypericum perforatum* L.), yellow starthistle	Greater flexibility, high spatial resolution, may operate below cloud ceiling	Limited amount of data	Lass et al. (1996); Thorp and Tian (2004)

[a] Abbreviations: CC, conventional color; CIR, color infrared; GPS, global positioning system; GIS, geographic information system.

Table 8. Removal mechanisms for robotic weed control.

Mechanism used	Study description	Reference	Advantages of system
Mechanical	Used rotating hoe as weed-control actuator for autonomous robot in sugar beet	Astrand and Baerveldt (2002)	No chemical threats, effective eradication of weed plants, applicable for weeds at all growth stages
	Studied the efficiency of mechanical actuators for weed control in sugar beet, cotton, broccoli, and other crop seedlings; damage hazard to main crops also studied	Garrett (1966)	
Chemical	Evaluated the potential of electrochemical thinner for selective herbicide application to control weeds	Cox and McLean (1969)	More economical, very specific in action, no soil disturbance, reduction in herbicide doses due to targeted application, avoids nontargeted herbicide actions, nonselective herbicides can also be used because of shielded mechanisms
	Declared targeted stream of herbicide better than total mechanical robotic removal as soil is less disturbed	McLean (1969)	
	Developed a prototype precision spray system that applied herbicide just to weeds in multiple crop rows. It was regulated by microcontroller-actuated valves	Lee et al. (1999)	
	Tested precision spray system in robotic weed control system for cotton and found it effective	Lamm et al. (2002)	
	Evaluated the efficacy of glyphosate application mixed with surfactants, keeping in view the microdrift and deposition in view and found that targeted robotic microsprayers are effective with least phytotoxic damage to main crops	Downey et al. (2004)	
	Studied targeted herbicide effectiveness against pigweed, spotted spurge [*Chamaesyce maculata* (L.) Small], and black nightshade (*Solanum nigrum* L.) and found it effective	Giles et al. (2004)	
Thermal	Flame weeding through robotics	Lalor and Buchele (1969)	Suitable for organic farming and conservation systems, least soil damage, effective against small weeds
	Developed and evaluated precision spray system to apply high-temperature organic soils to kill barnyardgrass, horse purslane, and black nightshade and found it highly effective	Giles et al. (2004)	
Electrical	Studied the potential of continuous current and electric shock to kill weeds	Diprose and Benson (1984)	No chemical or fire hazards, not much proximity to weeds required, very fast in action
	Used an end-effector with a high-voltage (15 kV) electrical discharge in a robotic weed control system	Blasco et al. (2002)	

technology, making it more suitable for precision weed management (Zhang and Kovacs 2012). The use of a UAV aided by a six-band multispectral camera was very successful for weed detection in a cornfield (Peña et al. 2013).

A successful case study on the use of UAVs for weed management in agronomic crops in Spain is worth sharing with details. Torres-Sánchez et al. (2013) directly utilized the UAV technology in site-specific weed management. It was suggested that UAV technology can play a vital role in early-season site-specific weed management in sunflower, corn, sugar beet, and tomato (*Solanum lycopersicum* L.) crops (Torres-Sánchez et al. 2013). After initial expertise in technical management, UAVs can provide very useful information for precision weed management in a very short time. The availability and efficient working of UAVs in agriculture also provide opportunities to ecologists for scale-appropriate measurements of ecosystems. Anderson and Gaston (2013) reviewed the UAV technology with a special focus on their use in framing spatial ecology. It was reported that a range of UAVs is available on the basis of size, structure, spatial specifications, camera position, mobility, and flight altitude. UAVs are mainly applicable in the fields of population ecology (Sarda-Palomera et al. 2012), vegetation dynamics (Getzin et al. 2012), and ecosystem processing (Mayer et al. 2012).

Robotics. With the advancement in robotics research for agriculture, it is now possible to use them for one of the least mechanized aspect, that is, weed control (Young et al. 2014). Weed control is no longer limited to the use of manual eradication or herbicide sprays but can now include the use of targeted operations of machines. Slaughter et al. (2008) reported the use of robotics for weed management, a revolutionary development with multiple benefits.

Robotic weed management is a four-step process, involving guidance, identification, precision robotic removal, and mapping of weed species (Young 2012; Young et al. 2014). The feasibility of a robotic weed-control system depends upon machine vision analyses, robotic efficiency/suitability, variable rate application technology, decision support system, and strength of weed-sensing tools, directly or indirectly (Slaughter et al. 2008; Young 2012). Guidance in row crops is accomplished with real-time kinematic GPS or through machine vision. This technique enables a researcher to detect the intensification of in-row weeds and helps to frame threshold levels for

applying control measures (Slaughter et al. 2008; Young 2012). Slaughter et al. (1999) used real-time color segmentation technology for guidance in direct-seeded lettuce, cotton, and tomato crops at different growth stages. Similarly, Kise et al. (2005) developed a guidance system on the basis of NIR stereovision, providing data of weeds in cereals but requiring some weed-free areas for calibration before actual guidance operation.

The machine vision directly depends upon climate conditions, farming practices, regional topographic differences, and cropping systems (Astrand and Baerveldt 2002; Slaughter et al. 2008). The bases for detection are classified as morphological features, spectral features, and visual textures. Morphological features of weed plants are considered as potential tools for machine vision detection, especially for distinction from other vegetation (Brown and Noble 2005; Søgaard 2005). Søgaard (2005) classified shepherd's purse, scentless mayweed, and wild mustard with great accuracy by using these active shape models. Plant reflectance is another successful indicator for weed detection through machine vision (Scotford and Miller 2005). Precise robotic weed removal on the basis of weed indication by guidance and detection is the next step. There might be the use of mechanical (Astrand and Baerveldt 2002), chemical (Lamm et al. 2002; Lee et al. 1999), thermal, or electrical (Blasco et al. 2002) approaches to remove weeds through robots. All the methods showed variable response regarding weed control; however, certain benefits are associated with each one (Table 8). Young et al. (2014) suggested automated weed control through robotics, a viable option for best integrated weed management in the future.

These technologies are no doubt the future of modern weed management and have a great role to play in precision agriculture. There is still a lot of research needed to optimize the technical requirements and to resolve the complex issues at the interface of weed spatial ecology and precision management.

Conclusions and Future Perspective

Weed management under changing climate and agricultural practices requires modern strategies. The nonjudicious use of chemical herbicides is causing environmental damage, health hazards, herbicide resistance in weeds, and nontarget actions. Thus, a set of alternative weed-management tools is needed under the prevailing conditions. The use of

nonconventional and possibly nonchemical weed-management strategies discussed above in an integrated manner can help on a sustainable basis. All these methods focus on environmental protection, practical viability, compatibility for integrated programs, and ecological stability. The right choice of one or more of these strategies according to geographic, agricultural, and socioeconomic conditions may offer an impressive weed control. None of them has the potential to comprehensively replace chemical weed management; however, an integrated approach may lead to success. The diversified nature of these strategies may be very useful against invasive and resistant weeds. Further research is needed to optimize these tools for improvement in efficiency and practical suitability. In the long run, a single weed-control measure may not remain effective and, thus, integrated weed management on the basis of advanced nonconventional strategies will be a pragmatic option in modern intensive agriculture.

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