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REVIEW

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Imperatives for integrated weed management in vegetable production: Evaluating research and adoption

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Abstract

Weeds have a significant impact on vegetable production worldwide. These intensive cropping systems feature frequent tillage, fertilization and irrigation, providing ideal growing conditions for crops as well as certain weeds. Integrated weed management (IWM) can reduce reliance on herbicides by encouraging a systems approach to weed management. Using insights from global research and industry literature, we investigated the effectiveness of prevailing weed control methods, and evaluated emerging management practices and technologies for ongoing research and adoption. Weed control relies primarily on a relatively narrow range of herbicides as well as frequent tillage. Herbicides have negative impacts on soil, water and human health, while tillage impacts soil quality and function. Intensive cropping on smaller plots facilitates IWM, relying on multiple strategies including hand weeding, mulches, cover crops and cultural methods (e.g., crop rotations, timing). New herbicide options are suggested as an industry priority but are constrained by the lack of new chemistry and potential herbicide resistance. Refinement and adoption of non-herbicide and emerging precision control methods into farm IWM in vegetables is more likely to be sustainable. This review is relevant to advanced vegetable production systems globally, but also to smallholder vegetable production in developing economies.

KEYWORDS

extension, herbicides, intensive horticulture, sustainability, tillage

1 | INTRODUCTION

Vegetable production occurs on intensively cropped land with frequent tillage and irrigation, and significant fertilizer amendment. These characteristics enhance weed germination and growth as well as their impacts on crop productivity, development and yield (Damalas, 2008; Melander et al., 2005; Mohler, 2001; Robinson, 2014). Crop varieties that compete poorly or are prone to weed contamination are particularly susceptible to weeds (Nerson, 1989; Swanton et al., 2009). Some weeds host crop pests, diseases and viruses (Brown & Gallandt, 2019; Coutts & Jones, 2005), while others interfere with crop management and harvesting (Henderson & Bishop, 2000; Kristiansen et al., 2015; Robinson, 2014; Sindel et al., 2011). The economic impact of weeds varies depending on crop type, however, labor (particularly associated with hand weeding) is the most significant weed management cost (Kristiansen et al., 2015; Melander et al., 2015; Valle et al., 2014).

This article summarizes current prevailing weed management techniques, as well as some techniques that are either under development or that have the potential for refinement to improve their effectiveness. It is based on a review of literature of previous and ongoing research, development and extension activity regarding different aspects of weed management in vegetable production systems. Wider adoption of these approaches as part of an integrated weed management (IWM) strategy can help to improve sustainability and weed management effectiveness in vegetable production.

2 | COMMON WEED CONTROL METHODS

2.1 | Chemical control methods

Herbicides are a mainstay of weed control in conventional vegetable production worldwide. Options include: pre-emergent or pre-plant products; herbicides to control selected weed species within specific crops after crop emergence; and non-selective products to control a broad range of weeds, used during crop fallows or applied selectively (Davis & Frisvold, 2017; Kristiansen et al., 2015; Melander et al., 2005; Robinson, 2014).

Pre-emergent herbicide effectiveness depends on crop and weed species, soil moisture levels, adherence to recommended application rates, amount of soil disturbance after application and timing of application (Landau et al., 2021). Post-emergent herbicides are more likely to be available for control of grass weed species in specific broadleaf crops, with few options available to selectively manage broadleaf weeds (Henderson & Bishop, 2000). Both pre-emergent and post-emergent herbicides are relatively expensive, but generally provide value for money since they are also highly effective (Kristiansen et al., 2015; Robinson, 2014).

Fallow herbicide application similarly appears to be an affordable and effective weed management strategy, and often involves using either a non-selective herbicide, or a herbicide that effectively targets site-specific problem weeds (Kristiansen et al., 2015). However, fallow herbicide applications are relatively less feasible in intensively cropped year-round systems due to a lack of time, while residual fallow herbicides can also damage the following crop if sufficient time is not allowed between herbicide application and planting (Fennimore et al., 2011). Spot spraying with non-selective herbicides is sometimes used to manage severe infestations or recently identified weeds. Non-selective herbicides (e.g., glyphosate) may be used for spot spraying of weeds in adjacent non-cropping areas such as irrigation channels, or for post-harvest field cleanup (Kristiansen et al., 2015). Shielded inter-row non-selective herbicide applications may be used instead of tillage to manage weeds between crop beds. Care is required to minimize the risk of crop damage through spray drift, and some vegetable growers are reluctant to employ shielded herbicide application for this reason (Coleman et al., 2015). Chemical fumigation may also be used to deplete the weed seed bank however this is increasingly considered a last resort due to soil, environmental and human health impacts (Chellemi, 2014; Hanson & Shrestha, 2006).

2.2 | Physical and mechanical control methods

Hand weeding may be conducted at various stages of the vegetable crop life cycle, but is most viable in support of other methods to manage weed survivors (Tiwari et al., 2021), or in smaller-scale systems. It can be very effective, though this depends on staff skill and diligence (Lee & Thierfelder, 2017; Onwude et al., 2016). It is also labor-intensive and very costly, and therefore not practical as a standalone or primary method of weed control (Pannacci et al., 2017). Effectiveness can also depend on weed species present; for example, hand weeding is likely to be less successful in the case of species that are capable of re-establishing from plant fragments (Peerzada, 2017; Soares et al., 2023).

Tillage is almost universally used in vegetable systems, commonly employed during crop fallows, and always during crop bed formation (Melander et al., 2015; Robinson, 2014). It may also be used at other times during the crop cycle depending on vegetable crop: (1) pre-plant tillage during and after bed forming; (2) post-plant inter-row tillage between crop rows; and (3) intra-row tillage before the crop canopy has closed (Kristiansen et al., 2015). Intra-row tillage is suited only to some vegetable crops, requiring specifically designed implements and precision guidance and/or experienced operators (Kristiansen et al., 2015; Pannacci et al., 2017; van der Werf et al., 1991).

Stale and false seedbeds involve forming crop beds in advance of crop planting, allowing weeds to germinate (if necessary combined with irrigation to encourage germination), and then controlling these one or more times using shallow pre-plant tillage, non-selective herbicides or thermal weed control. They are particularly useful in giving seed crops additional time to establish and out-compete the first post-seeding weed cohort, by establishing a seedbed that is relatively free of weed seed at depths from which they are likely to germinate (Gopinath et al., 2009; Lonsbary et al., 2003; Pannacci et al., 2017; Taylor, 2009). Where tillage is used to control recently germinated weeds, it should be carried out to a depth of not greater than 20 mm to prevent bringing more weed seed to the surface and encouraging a new flush of germination. Irrigation may be utilized where necessary to stimulate weed seed germination before control (Pannacci et al., 2017). An important drawback of these approaches is the time required to implement them—particularly in intensive year-round production systems on smaller land areas (Kristiansen et al., 2015).

In many vegetable crops, these physical methods are integrated in various ways to contribute to effective management of weeds before crop establishment and during the life of the crop. This is particularly the case in organic production systems, where stale or false seed beds may be used to reduce the weed seed bank before crop sowing or transplanting, while follow-up inter-row tillage, intra-row tillage and/or selective hand weeding may be utilized once the crop is established to control surviving weeds (Melander et al., 2015; Pannacci et al., 2017; Pannacci et al., 2018; Tiwari et al., 2021). Utilizing physical methods in this way has been shown to deliver effective weed management in vegetable crops, sustaining crop yields and providing an alternative to chemical weed control (Pannacci et al., 2017; Pannacci et al., 2018).

2.3 | Cultural control methods

Cultural methods used to manage weeds in vegetable crops include crop rotation, mulches, green manure crops and biofumigation, farm hygiene, thermal weed control and crop competitiveness (Brown & Gallandt, 2019; Melander et al., 2005; Robinson, 2014). The effectiveness of these approaches will vary in different production circumstances, and they may be used in various combinations (as well as being integrated with chemical, physical and mechanical approaches) to improve overall weed management success (Champagne, 2022; Pannacci et al., 2017).

Crop rotation is primarily used to manage crop disease, but also facilitates a more diverse weed management approach across the calendar year, for example by allowing access to different selective herbicide options (Koocheki et al., 2009; Robinson, 2014), providing the option of inter- or intra-row tillage through the growth characteristics of different crops, or by alternating between crops that provide lower and higher levels of weed competition (including non-vegetable crops) (Pannacci et al., 2017). Crop rotation is thus likely to be most effective when used in combination with other chemical, physical, mechanical or cultural methods before crop establishment and once the crop is growing. Crop rotation options may include different vegetable crops; or non-vegetable crops such as broadacre grains, sugarcane (*Saccharum officinarum* L.) and fodder crops (Koocheki et al., 2009; Kristiansen et al., 2015). A key benefit of crop rotation is that it may help to prevent the establishment of one or more dominant weed species as may occur in a monoculture production system (Pannacci et al., 2017), however this approach may not be feasible on all vegetable farms, for example where intensive year-round production of certain vegetable crops is required to meet buyer demand (Kristiansen et al., 2015).

Mulch options for vegetable production include plastic film, organic mulches and green manure cover crop mulches, with the goal of suppressing weed growth while retaining soil moisture and regulating soil temperature. In the case of plastic mulch film, supplementary methods such as hand weeding, inter-row cultivation or shielded/targeted herbicide application must be used to manage weeds between the crop beds, in the crop plant holes or where weeds have managed to pierce the film (Coleman et al., 2015; Henderson & Bishop, 2000). Plastic mulch is particularly effective in suppressing most weed species but is also expensive when purchase, application and disposal are accounted for. Its use therefore tends to be restricted to high-value crops such as cucurbits (Cucurbitaceae), eggplant (*Solanum melongena* L.) and capsicum (*Capsicum* sp.) (Brown & Gallandt, 2019; Kristiansen et al., 2015). Some hand weeding and chemical or mechanical control is still likely to be required to manage weeds between the crop rows, or in crop planting holes in the mulch film (Brown & Gallandt, 2019). Organic mulch options (e.g., cover crop residues, sawdust, wood chips, straw or sugarcane by-products and paper waste) can suppress weed growth with mixed levels of success, though are generally considered less effective than plastic mulch film (Campiglia et al., 2010; Kristiansen et al., 2015; Olsen & Gounder, 2001; Reberg-Horton et al., 2012; Soares et al., 2023).

Green manure or cover crops are used to improve soil quality and structure outside the normal cropping season. They may suppress weeds through competition for resources or allelopathic activity, and are likely to be most successful when they germinate and grow quickly, and form a thick canopy over the soil surface that limits the growth of weeds (Bond & Grundy, 2001; Büchi et al., 2020). Cover crop effectiveness as a weed management tool will also vary depending on cover crop species chosen, season in which the cover crop is grown, weeds present (extent and species), diligence in maximizing cover crop health and integration with other weed management methods (Adeux et al., 2021; Büchi et al., 2020; Jian et al., 2020; Rogers, 2007; Samedani & Meighani, 2022).

Farm hygiene practices are also an important component of effective IWM, in addition to limiting the spread of

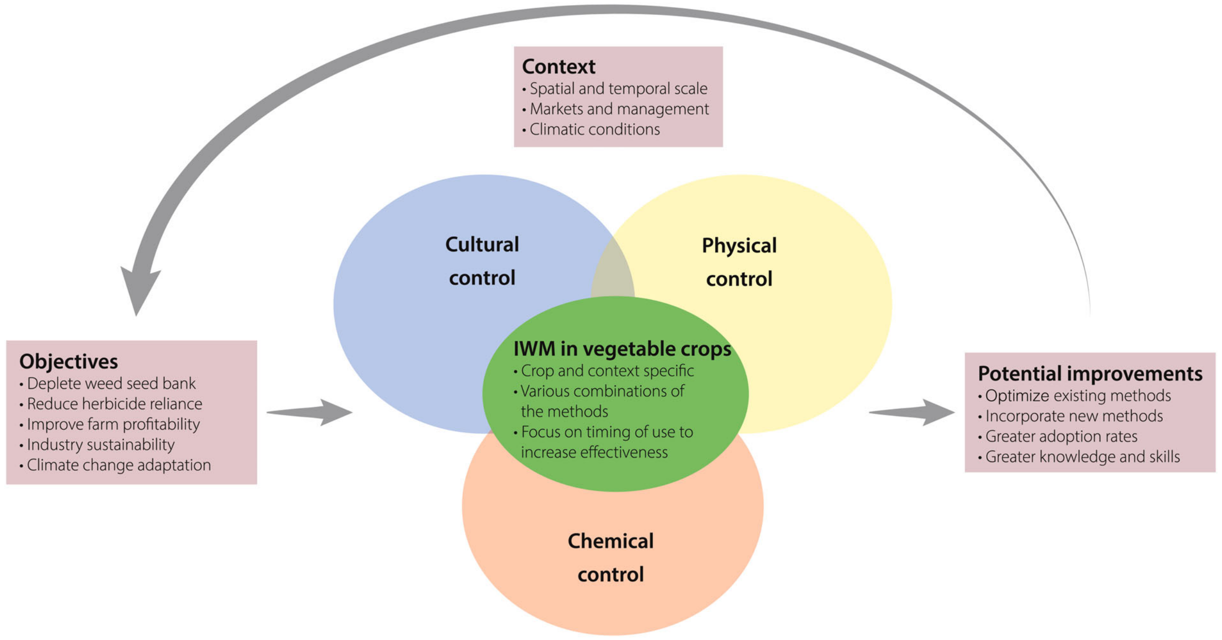

FIGURE 1 Conceptual diagram of integrated weed management in vegetable production systems.

other pests and crop diseases onto and within vegetable farms. Aspects of farm hygiene that can help limit weed spread include vehicle washdown, controlling weeds in adjacent areas and restricting machinery and people movement (Gill et al., 2018; Henderson & Bishop, 2000; Zoschke & Quadranti, 2002). Effective farm hygiene can be difficult to sustain or implement during prolonged wet weather, in flood-prone areas and in districts characterized by busy year-round production, and may be considered by growers to be redundant when a full spectrum of weeds are already present (Coleman et al., 2015; Kristiansen et al., 2015).

Thermal weed control methods using steam or flame equipment are most likely to be relevant to organic vegetable production or potentially on smallholder vegetable farms in developing economies, but these implements require a large amount of fossil fuel use, and appear to be less effective in managing monocotyledonous weeds (Candido et al., 2011; Lee & Thierfelder, 2017; Melander et al., 2005; Merfield, 2016). Increasing crop density to out-compete weeds may be effective in some cases, but in others crop plants may out-compete each other, with negative implications for final crop yield (Kristiansen et al., 2015).

2.4 | Integrated weed management in vegetable crops

IWM involves using a combination of weed control methods in a strategic way to reduce the burden of weeds (notably, by depleting the weed seed bank) and to reduce herbicide reliance (Asaduzzaman et al., 2019; Robinson, 2014; Zoschke & Quadranti, 2002). Previous research has shown that employing various combinations of IWM over a medium- to long-term can produce different results in terms of weed seed bank magnitude as well as species composition (Brown & Gallandt, 2019; Mohler et al., 2018; Sjursen et al., 2008). The constituent parts of an IWM program will therefore depend on context, especially management and climatic conditions (Figure 1).

Amongst conventional vegetable growers, pre- and post-emergent herbicide application, hand weeding and tillage may predominate in carrot (*Daucus carota* subsp. *sativus*), brassica (*Brassica* L.), celery (*Apium graveolens* L.) and lettuce (*Lactuca sativa* L.) crops, with plastic mulch not used. However in conventional cucurbit crops, plastic mulch is a cornerstone of weed management, supported by tillage, pre- and post-emergent herbicide use and hand weeding to remove occasional weeds growing through the mulch layer (Coleman et al., 2015; Kristiansen et al., 2015; Robinson, 2014). Organic vegetable growers rely on a range of non-herbicide weed control methods, including cover crops, tillage, hand weeding and maximizing crop competitiveness (Brown & Gallandt, 2019; Melander et al., 2005; Mohler et al., 2018).

Timing is a critical element of IWM—too early and some weeds may re-establish in the crop; too late and weeds may be too large to control effectively. This is well known in terms of individual control methods (Tei & Pannacci, 2017). However it also applies to implementing

IWM, where the temporal scale is greater than the current season and requires the consideration of factors such as crop sequencing based on prevailing weed loads, assessing whether delays due to stale seed beds are worthwhile, minimizing seed production in late-season weeds, and building soil fertility over time to improve crop vigor and health (Merfield, 2023).

Timing the implementation of different weed management methods also impacts on the potential for crop damage (Fennimore et al., 2011). In the case of physical and mechanical weed control, the risk of crop damage increases later in the crop life, as larger crop plants are generally more prone to damage from most weed management activities than smaller crop plants (Cordeau et al., 2017; Tiwari et al., 2021). Application of pre-emergent herbicides may be timed in such a way that crops establish and have a greater capacity to outcompete later weed cohorts (Landau et al., 2021). Most techniques are only suitable at certain times in the crop cycle, or for particular management circumstances and personal preferences (Kristiansen et al., 2015; Zoschke & Quadranti, 2002), hence the need to integrate several techniques effectively to ensure frequent intervention in vegetable crops to suppress weeds using "many little hammers" (Liebman & Gallandt, 1997).

3 | FACTORS LIMITING THE SUSTAINABILITY OF COMMON WEED CONTROL METHODS

Several of the key weed control techniques outlined in the previous section of this article appear poised to be less effective in the near future, while others may pose environmental risks and threaten the sustainability of intensive vegetable production systems.

Repeated use of herbicides with the same mode of action (MOA) can lead to herbicide resistance in weed populations, a global problem (Broster et al., 2019; Evans et al., 2016; Heap, 2022) exacerbated by adoption of herbicide-tolerant crop varieties (Asaduzzaman et al., 2019; Iqbal et al., 2019). Several of the most significant weeds of vegetable production have demonstrated herbicide resistance (Asaduzzaman et al., 2019; Heap, 2022; Iqbal et al., 2019; Jalaludin et al., 2010; Owen & Powles, 2009; Pratley et al., 2008; Seng et al., 2010), though the risk posed to vegetable growers may be somewhat less than in arable crop production due to greater use of tillage and the use of multiple weed management strategies that is more a feature of vegetable production (Boyd et al., 2022; Riemens et al., 2022).

Selective herbicide control of dicotyledonous weeds can be challenging in vegetable production because the majority of vegetable crops are also dicotyledonous (Kristiansen et al., 2015). Herbicides can also have off-target impacts on the natural environment (Duke et al., 2012; Gunstone et al., 2021; Kraus & Stout, 2019; Melander et al., 2005; Motta et al., 2018), impact crop health, disease resistance and crop nutrition (Duke et al., 2012; Kanissery et al., 2019; Martinez et al., 2018), and pose risks to human health (Bai & Ogbourne, 2016; Gillezeau et al., 2019). It is therefore desirable to reduce reliance on herbicides in vegetable crop production where this is possible, or to utilize herbicides in a more precise fashion (including applying them at recommended rates) to improve efficiency, reduce the risk of crop damage and off-target damage, and reduce the risk of herbicide resistance emerging.

Recent estimates suggest that over 7 million tons of plastic mulch film is used annually in crop production globally (FAO, 2021; Sintim & Flury, 2017). However, the long-term viability of this approach is questionable, due to environmental problems associated with mulch disposal (Limpus, 2012; Qi et al., 2020), and microplastic contamination of food chains (FAO, 2021; Sintim & Flury, 2017). Frequent tillage is a critical aspect of both conventional and organic vegetable production, though excessive tillage can negatively impact soil quality such that less intensive approaches are preferable (Brown & Gallandt, 2019; Lee & Thierfelder, 2017).

4 | WEED MANAGEMENT RESEARCH AND ADOPTION PRIORITIES FOR VEGETABLE PRODUCTION SYSTEMS

Due to the unsustainability of certain common weed management techniques in vegetable production systems, alternative weed management processes are likely to be required (Marí et al., 2020; Sintim & Flury, 2017), with a focus on non-herbicide weed control approaches included as aspects of a sustainable and user-friendly integrated weed management (IWM) approach (Neve et al., 2018).

Based on our earlier research on weed management research and adoption priorities in Australian vegetable production systems (Kristiansen et al., 2015), and subsequent industry developments described in this article, we identify a variety of knowledge gaps for weed management specific to vegetable production (Table 1). These priorities are unlikely to be comprehensive and it may be possible to rate or rank their relative importance in different contexts and vegetable production systems to best utilize scarce research, development and extension resources, however that is outside the scope of this review.

TABLE 1 Research and adoption priorities for weed management in vegetable production systems.

Herbicide control
New herbicide options
Identify the extent of herbicide resistance in vegetable production
Non-chemical and precision control
Management approaches for specific problematic weed species
Precision weed management, field robotics
Reduced or zero tillage, semi-permanent or permanent crop beds
Biodegradable mulch films
Improve and adopt physical and cultural methods (weed seed bank depletion; cover crops; hand weeding; intra-row tillage; stale and false seedbeds)
Integrated weed management

4.1 | Herbicide control

Accessing *new herbicide options* is an important research priority to vegetable growers (Kristiansen et al., 2015). However, introduction of new herbicides into vegetable crops is restricted by the diversity of crop and weed combinations characteristic of vegetable production, limited number of suitable products and alternative chemistry (including new MOAs), and relatively small and fragmented industry segments which may make the effort required to pursue new herbicides uneconomic (Coleman et al., 2015; Davis & Frisvold, 2017; Fennimore et al., 2014; Kristiansen et al., 2015). Therefore, despite new herbicide options being a top research priority from the industry standpoint, for the preceding reasons there is only a moderate chance that vegetable growers will obtain access to many new options.

The likelihood of *herbicide resistance* in vegetable cropping may be lower than in other production systems, partly due to the diversity of weed control methods used in this system (Fennimore et al., 2014; Pannacci et al., 2017; Riemens et al., 2022). Nonetheless, there is concern that herbicide resistance is becoming a more important issue in vegetable crops (Boyd et al., 2022). At least in the Australian case, resistance to glyphosate is a particular concern, given that most conventional growers rely on this herbicide heavily for fallow and precision weed management. Other commonly used herbicides of concern included pendimethalin and s-metolachlor (Kristiansen et al., 2015). Research and adoption/extension activity to manage herbicide resistance in vegetable systems may focus on: mapping the severity and extent of herbicide resistance in vegetable industries; optimizing application methods and rates to ensure that herbicides are used as efficiently as possible within guidelines; refining and extending MOA rotation schedules; maximizing the effectiveness and adoption of diverse non-chemical methods; and addressing resistance at spatial scales larger than the individual farm (Broster et al., 2019; Evans et al., 2016; Evans et al., 2018; Korres et al., 2019).

4.2 | Non-chemical methods and precision control

Some research has been already completed regarding *management of specific weed species* of significance to vegetable production, including tailored management options, or in some cases options for localized eradication, of specific widespread or locally significant weed species (e.g. Bangarwa et al., 2008; Riemens et al., 2008; Sturm et al., 2016). However, more information could be developed on the impact and specific management strategies for particular weed species in vegetable production. This information could be extended to vegetable growers, allowing them to implement "tailored IWM" to address their most significant weed species problems.

Precision weed management, most notably field robotic systems (Melander et al., 2015; Steward et al., 2019; Sukkarieh, 2016; Utstumo et al., 2018) have the potential to automate a significant portion of weed management activity. The economic feasibility of current and emerging digital agriculture systems for vegetable farms which are generally small will require further study as the technology continues to evolve (Melander et al., 2015; Young et al., 2017). Field robotic systems were becoming available on the market at the time of writing; however, some of the limitations of these systems included their high unit cost, successful differentiation of weeds from bare ground or crop plants under changing field conditions, and the need to tailor the systems to relatively specific subsets of weeds and crops (Zhang et al., 2022). However the considerable research and development effort already underway for field robotics appears poised to deliver a viable and more affordable product over the next few years (Merfield, 2023).

Reduced tillage involves less frequent cultivation and/or tillage at reduced depths (semi-permanent crop beds), while *zero tillage* involves establishing permanent crop beds. Key benefits of these approaches include improved soil biodiversity, fertility and structure, and farm system sustainability (Mäder & Berner, 2012; Pieri, 2002), and they are more likely to be utilized in organic vegetable production (Chen et al., 2017). Despite industry concerns that reducing tillage frequency may actually increase the weed burden, its potential benefits in improving weed management have been demonstrated, for example by combining this approach with cover crops grown outside of the cash crop growing season (Büchi et al., 2020; Chen et al., 2017). Establishing semi-permanent or permanent crop beds in vegetable production under a reduced or zero tillage regime requires growers to use precision systems such as Global Positioning System (GPS) farm machinery tracking (Rogers, 2007). Nonetheless, the feasibility of these approaches will depend on their potential role in contributing to the issue of growing weed resistance to non-selective herbicides such as glyphosate, whose use is likely to be a central feature of these systems as a replacement for tillage in managing weeds post-harvest and while preparing for the next crop (Jaskulska et al., 2020; Morris et al., 2010; Übelhör et al., 2014).

Biodegradable mulch films are likely to require further research and development to achieve commercial viability (Cirujeda et al., 2012; Hayes et al., 2019; Limpus, 2012; Razza & Degli Innocenti, 2012). This may include: exploring means of reducing the cost of their production; improving their effectiveness in different climates and conditions; determining how to apply and work with currently available products more effectively (for example to avoid having the film break down too early); improving the successful, complete biodegradability of the film; and understanding what happens to mulch pieces in the soil as they break down (Kristiansen et al., 2015; Marí et al., 2020; Tofanelli & Wortman, 2020). As this technology becomes more viable and cost-effective and its performance improves relative to conventional plastic mulch, adoption rates may increase in systems where conventional films are currently a key feature of soil and weed management.

Other physical and cultural weed control methods appear worthy of further research to better understand their impacts, and to understand how they may be better combined with chemical and mechanical methods to improve IWM in different production contexts. Industry capacity-building and awareness-raising activity may also be warranted to increase rates of adoption of these methods among growers. Relevant methods include (Bastiaans et al., 2008; Korres et al., 2019; Kristiansen et al., 2015):

- Weed seed bank management—managing weeds before seed production and depleting the existing weed seed bank to reduce weed germination rates;
- Cover crops—understanding the effects of different non-biofumigant and biofumigant cover crop varieties for weed suppression, in comparison to more conventional fallow weed management practices;
- Hand weeding—identifying any potential gains in efficiency, considering different hand weeding implements, timing of intervention and integration with other methods (in particular, used to follow up on surviving weeds rather than as a central method of a vegetable IWM strategy);
- Intra-row tillage—refinement and adoption of the technology as an alternative to intra-row hand weeding and/or selective post-emergent herbicides; and
- Stale and false seed beds—exploring their viability in intensive year-round production systems.

4.3 | Integrated weed management

As has been summarized in this article, previous research demonstrates that IWM can be highly effective in reducing the burden of weeds in vegetable production systems. There are many different combinations of chemical, physical, mechanical and/or cultural weed control practices that may constitute IWM in different vegetable production systems. In all cases, however, the central goal of IWM on vegetable farms should be to manage the weed seed bank in the soil through all relevant management practices to deplete the number of existing weed seeds, and avoiding where possible further inputs by preventing weeds from setting seed (Auškalnienė et al., 2018; Gallandt, 2006).

In addition to improving management of weed seed banks on vegetable farms, improvement in implementation and adoption of IWM may be sought to reduce reliance on herbicides, manage the risks associated with herbicide resistance and adopt a greater diversity of non-chemical methods (including technological innovations but also tried and true approaches) to help adapt to and mitigate climate change (Birthisel et al., 2021; MacLaren et al., 2020; Young, 2020; Young et al., 2017). Developing and extending IWM in intensive vegetable production and refining and improving non-herbicide techniques in support of this objective, may be at least as beneficial as searching for new herbicide options, and is likely to be more feasible and sustainable.

Low adoption rates have been attributed to the relative complexity of IWM which involves appropriate timing and trade-offs of several cultural, physical and chemical methods (e.g. Bastiaans et al., 2008), in contrast to a relatively straightforward conventional weed management approach with herbicides and tillage as its cornerstones. Maximizing adoption of best practice IWM needs to take into account vegetable grower priorities, skills and resources, willingness to make change and other factors that may be hampering their adoption of IWM (Bastiaans et al., 2008; Neve et al., 2018). Broadacre cropping systems are likely to provide lessons for developing and upscaling IWM strategies in vegetable production. Technological advances such as the field robotics systems discussed in this article will also play a significant role, particularly in developed economy vegetable production systems. Ecological weed management approaches are an increasing focus, underpinned by the principle of maximizing crop productivity and restricting the impact of weeds by focusing on gradual depletion of the weed seed bank, while restricting any negative environmental impacts of weed management activity (Bastiaans et al., 2008; Birthisel et al., 2021; MacLaren et al., 2020). The weed control techniques that are the focus of the research and adoption priorities discussed in this review lend themselves to inclusion in more refined IWM and ecological weed management approaches on vegetable farms.

5 | CONCLUSION

IWM on vegetable farms encourages a systems approach to weed management and can contribute to the sustainability of the industry by reducing grower reliance on herbicides. Many of the areas for research and adoption activity identified in this article are likely to be most relevant to IWM practices in intensive vegetable cropping in developed countries, where more complex IWM strategies and emerging precision technologies such as field robotics may be more economically feasible (FAO, 2006). In developing economies and smallholder vegetable production, even common weed management inputs such as herbicide and plastic mulch tend to be less affordable. Nonetheless, the general principle of adoption of IWM applies to all vegetable farms, and can be implemented using myriad techniques—for example, mechanical approaches such as utilizing animal-driven tillage implements and hand weeding in place of herbicides and plastic mulch in developing economies (Lee & Thierfelder, 2017), which can still form the basis of an effective IWM strategy if timed appropriately and utilized diligently.

Regardless of technological and resource availability, the central goal of IWM should be to deplete the weed seed bank in the soil through all suitable and accessible chemical, mechanical, physical and cultural management practices, used in optimal combinations and at times in the crop cycle likely to achieve the most effective outcome (Auškalnienė et al., 2018; Gallandt, 2006; Lee & Thierfelder, 2017), and with minimal environmental impact (Bastiaans et al., 2008; Birthisel et al., 2021). Herbicides are likely to remain highly desirable in achieving this end where they are available. They remain relatively affordable and cost-effective and will remain a key component of IWM in conventional vegetable production—although are unlikely to take on a more central role in the future. Worldwide, herbicide availability for the wide variety of vegetable crops is likely to remain limited, and growers need to avoid over-reliance on the limited range of registered herbicides available, particularly in the context of the growing problem of herbicide resistance (Kristiansen et al., 2015; Moss, 2017; Robinson, 2014).

The greatest gains appear to be available in further refinement and greater adoption of other weed management practices to underpin more successful and sustainable IWM. Some of these methods are relatively novel and still under development, while others have been available to vegetable growers for a long time and are likely to become more important given the need to better support herbicide usage with other diverse methods. They include but are not limited to: cover crops; hand weeding; inter-row tillage; stale and false seed beds; field robotics; biodegradable mulch films and potentially thermal weed seed bank destruction. Focusing research and adoption efforts on these and other non-herbicide practices, as well as optimal timing of intervention and combination of methods in different circumstances, will help to enhance the sophistication of IWM in vegetable production, and reduce reliance on a more conventional and less sustainable approach that centers on chemical weed control, tillage and plastic mulch.

AUTHOR CONTRIBUTIONS

All authors named on this manuscript contributed to the research design, development of the research topics, review of the literature and development of the list of priority areas for future work. All authors have agreed to the publication of this, the final version of the manuscript, and agree to be accountable for all aspects of the work contained in this manuscript.

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