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REVIEW PAPER

Precision weed management in maize

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Abstract: Weeds are the largest biological constraint on maize productivity, and management based on uniform herbicide spraying and repeated hand weeding is becoming costly, labour-intensive and environmentally questionable. Precision weed management (PWM) adjusts the place, timing, dose and method of control to the spatial and temporal variability of weeds within a field. This review summarises the weed problem in maize, with emphasis on Indian conditions, and describes the sensing platforms, deep-learning classifiers, spot and patch sprayers, camera-guided hoes and robots that make up current PWM systems. Field evidence shows herbicide savings of at least 50% with patch spraying, and an average of 59% reported for commercial camera-based sprayers in corn, soybean and cotton, although savings depend strongly on weed pressure. Adoption is held back by cost, poor interoperability between sensors and machines, data demands and a gap between research and on-farm practice. Combining PWM with integrated weed management, timing control to the critical period and using low-cost, service-based delivery appears the most realistic route for smallholder maize systems.

Keywords: Deep learning • Maize • Precision weed management • Robotic weeding • Site-specific weed management • Spot spraying • UAV

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Introduction

Maize (*Zea mays* L.) is grown across a wide range of environments and is the third most important field crop in India after rice and wheat (Rani *et al*., 2022). Because it is sown in wide rows and grows slowly in the first weeks after emergence, the crop is a weak competitor against early weeds, so weed infestation remains one of the main reasons why farm yields fall short of yield potential.

Farmers still depend largely on blanket herbicide applications and repeated hand weeding. Both treat the field as if weeds were spread evenly, yet weeds usually occur in patches whose size and species composition change from season to season (Gerhards *et al*., 2022). Uniform treatment wastes herbicide in clean areas, raises production cost, adds to the environmental load and keeps selection pressure for resistance high, while hand weeding is increasingly limited by labour shortages (Rani *et al*., 2022).

Precision weed management responds to this variability. Advances in cameras, unmanned aerial vehicles (UAVs), computing and artificial intelligence now make it possible to identify weeds and to apply control only where and when it is needed (Allmendinger *et al*., 2022; Gerhards *et al*., 2022). This review outlines the weed problem in maize, the technologies behind PWM, the evidence on their performance, their integration with integrated weed management (IWM), and the barriers to adoption, with attention to Indian conditions.

The weed problem in maize

In India, weeds cause the highest crop loss among biotic constraints (about 33%), ahead of pathogens (26%) and insects (20%) (Rani *et al*., 2020). The damage is greatest early in the season: the critical period of weed competition in maize starts about 17 to 29 days after planting, at an

acceptable yield loss of 5–10% (Rani *et al*., 2020). Weeds also take up nutrients quickly. In one study, weeds removed 59 kg N, 10 kg P_2O_5 and 59 kg K_2O per hectare during the first 30 days of maize growth, which was seven to ten times more than the crop itself (Rani *et al*., 2022).

The usual practice is a pre-emergence herbicide such as atrazine or pendimethalin followed by one hand weeding (Rani *et al*., 2020). Where labour is scarce, atrazine applied pre-emergence followed by topramezone or tembotrione post-emergence has proved effective and economical (Rani *et al*., 2022). These programmes are applied uniformly, so every part of the field receives the same treatment whether weeds are dense, sparse or absent. This is the inefficiency that PWM aims to remove.

Concept and components of precision weed management

A PWM system links three elements: (1) sensors and classifiers that detect and identify weeds, (2) decision algorithms that decide whether control is needed and choose the method and rate, and (3) a precise actuator, such as a sprayer with boom-section or single-nozzle control, a hoe or a robot (Allmendinger *et al*., 2022). Gerhards *et al*. (2022) describe similar systems built on 3D cameras, multispectral imaging and artificial intelligence, combined with precise spraying and hoeing aimed at weed patches or individual plants. Looking ahead, weed scientists expect weed management to rely on such technologies together with ecological understanding, rather than on herbicides alone (Westwood *et al*., 2018). Figure 1 shows how these elements fit together as a sense–decide–act–record cycle, and Table 1 summarises the main technologies discussed below.

The decision step is where agronomic knowledge enters the system. A sensor can say where weeds are and, ideally, which species; it cannot say whether treatment is worthwhile. That judgement depends on the crop stage relative to the critical period, the competitiveness of the species present, the expected cost of control and the risk of leaving escapes that set seed. Simple rules, such as treating any cell of a weed map whose weed cover exceeds a chosen threshold, are a practical starting point, and more advanced models can add species, dose and economics (Allmendinger *et al*., 2022; Gerhards *et al*., 2022). Because maize is most vulnerable early, decision rules for maize should be tied explicitly to crop growth stage rather than to calendar dates alone.

Weed detection and mapping

UAV-based mapping

UAV imagery gives very high spatial resolution early in the season, when post-emergence decisions are made. In an experimental maize field in Spain, an object-based analysis of six-band multispectral UAV images produced a weed map with 86% overall accuracy for three weed-

Table 1. Main technologies used in precision weed management and their typical strengths and limits

Technology	What it offers	Main limitation	Key sources
UAV multispectral/RGB mapping	Early-season weed maps for site-specific treatment; in maize, a three-class map reached 86% overall accuracy	Needs flight timing, image processing and a way to pass the map to the sprayer	Peña *et al*. (2013); López-Granados *et al*. (2016)
Ground cameras with deep learning	Real-time, species-level detection, including green-on-green; CNNs tested in maize	Needs large labelled datasets; computing load limits speed	Hasan *et al*. (2021); Peteinatos *et al*. (2020)
Spot and patch sprayers	At least 50% herbicide saving in various crops; 59% average reported for commercial units in corn, soybean and cotton	Savings fall when weed pressure is high; manufacturer data need independent checks	Gerhards *et al*. (2022); John Deere (2024); Iowa State Univ. (2024)
Camera-guided hoes	Higher selectivity and efficacy than manually steered hoeing; widely available for row crops	Mainly inter-row; intra-row control is harder	Machleb *et al*. (2020); Gerhards *et al*. (2022)
Weeding robots	Autonomous, chemical-free or targeted treatment	Struggle with changing field conditions; full automation still distant	Machleb *et al*. (2020)

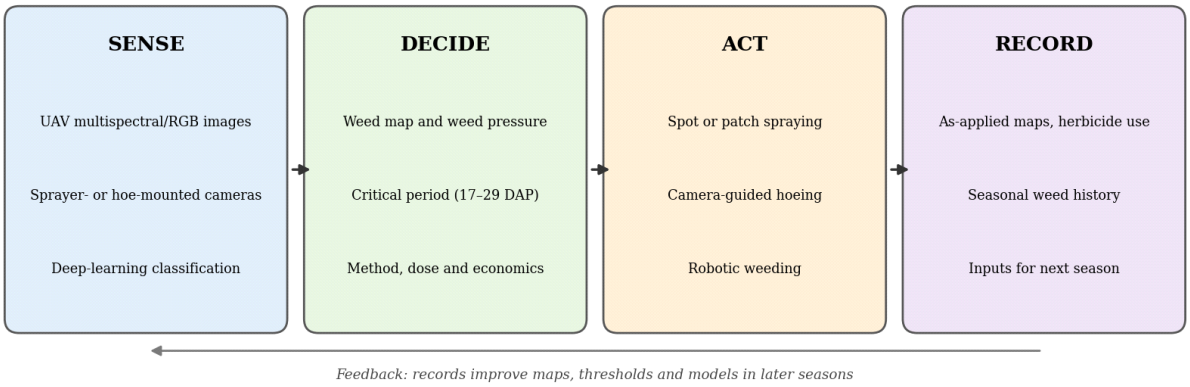


Figure 1. Conceptual workflow of a precision weed management system for maize (DAP = days after planting)

cover classes. About 23% of the field was weed-free and a further 47% had low weed cover (below 5%), which pointed to a large potential saving in herbicide (Peña *et al*., 2013). In another maize study, maps of johnsongrass (*Sorghum halepense*) patches indicated potential herbicide savings of 85–96% (López-Granados *et al*., 2016). Such maps are most useful for perennial or patchy weeds; their value falls when weeds are dense and uniform.

Ground-based machine vision and deep learning

Cameras mounted on a sprayer or hoe can classify plants in real time. The main difficulty is the green-on-green problem: crop and weeds often have similar colour, shape and texture at early growth stages (Hasan *et al*., 2021). Deep learning, particularly convolutional neural networks (CNNs), has largely replaced hand-crafted image features. Most studies use supervised learning with pre-trained models fine-tuned on plant datasets, and accuracy is high when large amounts of labelled data are available (Hasan *et al*., 2021). Peteinatos *et al*. (2020) applied CNNs to weed identification in maize, sunflower and potato. The main weaknesses are the cost of building labelled datasets and the tendency of models to perform worse under lighting, soil, growth stage and weed species conditions that differ from those used in training.

Mapping versus real-time sensing

The two approaches answer different needs. Mapping from UAV images separates sensing from application, which allows time for analysis and gives a field-wide view of weed patches, but it needs an extra operation, georeferenced prescription files and a sprayer able to read them. Real-time sensing on the machine removes that delay and requires no separate flight, but the camera, computer and nozzle control must work together at working speed, and the classifier must perform reliably in every field encountered (Allmendinger *et al*., 2022). In practice, the choice depends on weed biology, field size, the equipment available and how quickly weeds emerge after planting. Mapping is attractive for patchy perennial weeds, whereas real-time systems suit flushes of annual weeds that appear repeatedly during the critical period.

Site-specific chemical control

Site-specific spraying takes two main forms. Patch spraying treats mapped areas of higher weed density, while spot spraying switches individual nozzles on or off for single plants or small clusters. Systems are also grouped by what they can distinguish: green-on-brown sensors separate green vegetation from soil and crop residue and suit pre-plant or fallow use, whereas green-on-green systems separate weeds from the living crop and therefore need image classifiers such as CNNs (Allmendinger *et al*., 2022).

Gerhards *et al*. (2022) report that patch spraying saved at least 50% of herbicide in various crops without raising weed-control costs in the following years. Commercial camera-based sprayers have since reached farms. John Deere's See & Spray, introduced in 2021, opens individual nozzles when boom-mounted cameras detect weeds, and the company reported an average herbicide saving of 59% on corn, soybean and cotton fields across more than one million acres in 2024 (John Deere, 2024). Independent field-scale trials by Iowa State University on five soybean fields (415 acres) gave an average product saving of 76%, with a lowest field result

of 43.9%, and found that savings depended on initial weed pressure and were highest when pressure was low at the second herbicide application (Iowa State University, 2024). These figures are encouraging for maize, but the manufacturer's numbers are self-reported and the independent trial was in soybean, so maize-specific, farmer-field data are still needed.

Precision application also changes how resistance and product selection are managed. When only part of a field is sprayed, fewer weeds are exposed to a given mode of action, and records of where each product was applied can inform rotation and mixture decisions in later seasons. Treating only weedy areas can also make it economical to use a more specific or higher-cost product on those areas, but this depends on registration, label conditions and local costs, which differ between countries and need checking before any programme is adopted.

Mechanical and robotic weeding

Where herbicide use must be reduced or avoided, sensor-guided mechanical weeding is an alternative. Camera-guided hoeing improved selectivity and weed-control efficacy compared with manually steered hoeing (Gerhards *et al*., 2022). Camera-steered hoes with hydraulic side-shifting for row crops are robust and now widely available from several manufacturers (Machleb *et al*., 2020). The wide rows of maize suit inter-row hoeing, whereas weeds within the row are harder to remove without damaging the crop. Robotic platforms are developing fast, but they still struggle with the ever-changing conditions of real fields, and fully automated systems may not exist for many years (Machleb *et al*., 2020). For now, hoes and sprayers fitted with sensors are the most practical mechanical options.

Integration with integrated weed management

Precision tools work best as part of IWM rather than as a replacement for it. Three links are especially relevant for maize. First, timing: because the critical period begins within the first three to four weeks (Rani *et al*., 2020), sensing should be scheduled for this window so that corrective action can be taken before yield is affected. Second, herbicide programmes: a pre-emergence residual herbicide can protect the crop during early growth, with a targeted post-emergence pass applied only where sensors show weeds. This approach saves most when early weed control has been successful and weed pressure is low at the later application (Iowa State University, 2024). Third, non-chemical practices such as suitable row spacing, vigorous crop establishment, mulching and cover crops lower the weed pressure that precision tools must handle. Weed maps collected over several seasons can also guide long-term decisions on herbicide choice, rotation and field-specific management.

Economic and environmental benefits

The main economic benefit is lower herbicide use, and with it lower input cost and spray time, without more weeding cost in later years (Gerhards *et al*., 2022). Environmentally, reduced use limits chemical load on soil and water and eases selection pressure for resistance. PWM is also seen as an efficient tool for meeting regional pesticide-reduction targets (Allmendinger *et al*., 2022). Savings are not guaranteed, however. They shrink when weeds are dense and uniform, and equipment, software and service costs must be set against them. A realistic assessment should therefore compare whole-season costs and weed-control outcomes with those of the conventional programme for the same field.

Challenges and barriers to adoption

Despite strong research results, farmers' use of site-specific weed management is limited and does not match scientific progress, especially in real-time identification and mapping (Lati *et al*., 2021). A recent bibliometric analysis of 563 studies found that most work focuses on weed detection, and only 40 papers treat site-specific herbicide application as a complete workflow of detection, decision and application under realistic field conditions, with few on-farm studies and little farmer involvement (Rasmussen, online first). Further obstacles include poor interoperability between sensors and controllers (Gerhards *et al*., 2022), dependence on large labelled datasets (Hasan *et al*., 2021) and limited crop availability of commercial systems, which are currently offered for corn, soybean, cotton and fallow (John Deere, 2024).

For Indian maize, additional constraints are likely to include small and fragmented holdings, the high capital cost of imported machines, limited technical support, and the need for models trained on local weed species

and cropping systems. These are the authors' inferences rather than findings from the cited studies, and they need to be tested. At the same time, acute labour scarcity (Rani *et al*., 2022) strengthens the case for mechanised and sensor-based options. Custom-hiring services, shared UAV mapping and low-cost sensors are plausible ways to give smallholders access without individual ownership.

Future prospects

Priorities include (i) standardised communication between sensors, controllers and sprayers, such as the ISOBUS-based approach proposed for spot sprayers (Allmendinger *et al*., 2022); (ii) open, regionally diverse and well-annotated image datasets, and models that generalise across fields, seasons and sensors; (iii) on-farm trials in maize that measure weed control, yield, herbicide use and cost together (Lati *et al*., 2021; Rasmussen, online first); (iv) decision support that combines weed maps with critical-period timing, herbicide resistance risk and economics; and (v) affordable machines and service models designed for small farms. Closer collaboration among weed scientists, engineers, economists and farmers will be needed to turn these technologies into routine practice (Westwood *et al*., 2018).

Conclusion

Precision weed management can reduce herbicide use, lower costs and ease reliance on scarce labour in maize, by treating weeds where and when they matter rather than treating the whole field uniformly. Evidence from UAV mapping, deep-learning detection, spot spraying and camera-guided hoeing is promising, with herbicide savings of at least 50% reported in various crops, but results depend on weed pressure, and maize-specific field data remain limited. Wider adoption will require interoperable equipment, locally trained models, affordable delivery models and on-farm validation. Integrating PWM with timely, critical-period-based IWM is the most practical path for sustainable maize production.

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