Recent Trends in Integrated Weed Management Practices for Sustainable Farming Systems

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ABSTRACT

Conventional weed management relies on selective herbicides, biological control and allelopathy but faces limits from herbicide resistance, labour decline and climate change. Rapid advances in AI, UAVs, cameras and sensors drive Smart Weed Management (SWM) to map and target weed variability, cutting herbicide use and labour costs. SWM integrates organic bioherbicides, judicious organic or inorganic fertilizers and practices like alternate wetting and drying to reduce emissions and earn carbon credits. Computing, robotics and big data enhance precision control and decision making. Education of future weed scientists and farmer behaviour change are critical for adoption. Policy support, extension and research collaboration are needed to scale SWM. Together, conventional and smart methods offer resilient, low input weed control for diverse countries.

INTRODUCTION

Weed science is the study of weed biology and ecology underpins Integrated Weed Management (IWM), combining biological, chemical, cultural and mechanical methods to combat herbicide resistance and protect yields. Conventional herbicide-based approaches dominated the 20th and early 21st centuries but are strained by climate change, rising CO_2, temperature effects on C_3 and C_4 dynamics and shrinking agricultural workforces. Rapid advances in AI, UAVs, multispectral RGB cameras and proximal remote sensing enable Smart Weed Management (SWM) to map and target weeds precisely. SWM expands IWM through precision weed control, IT and robotics, aiming to cut herbicide use, labour and emissions. Carbon smart practices like alternate wetting and drying (AWD) can link weed control to carbon credits. This article summarizes conventional methods and advocates SWM adoption for sustainable, low input weed management.

Conventional Weed Management

Cultural weed control methods include hand weeding, flaming, mulching, cover cropping, intercropping and soil solarization. Although these practices are more labour-intensive and time-consuming than herbicides, they are cost effective, easy to adopt and environmentally acceptable to farmers (Gazoulis *et al*., 2021). By improving crop competitiveness and promoting desirable vegetation, cultural methods help suppress weed growth and play an important role in integrated weed management (Menegat & Nilsson, 2019).

Smart Weed Management Approaches

The extensive use of herbicides has raised concerns regarding environmental pollution, unsafe agricultural practices and potential risks to human health. In many countries, the agricultural workforce has declined considerably over the years, creating a need for labour-saving and efficiency enhancing technologies. For instance, the share of agricultural labour in Vietnam decreased substantially between 2005 and 2016, while similar trends have been observed in Japan, accompanied by an ageing farming population (Nguyen *et al*., 2020). To address these challenges, precision weed management technologies are gaining importance. Weed mapping helps identify and locate weed infestations, enabling site-specific herbicide application and reducing unnecessary chemical use and costs (Esau *et al.,* 2021). Likewise, sensors provide real time information on soil and crop conditions, allowing efficient management of irrigation and nutrient inputs. Multispectral cameras can detect crop stress at an early stage and accurately distinguish crops from weeds, thereby improving the precision and effectiveness of weed control operations (Gerhards *et al.,* 2022).

Precision Weed Management

Agricultural weed management faces several challenges, particularly due to labour shortages and rising production costs. Manual thinning is highly labour intensive, requiring substantial time and effort, whereas the combination of machine thinning and manual weeding can significantly reduce labour requirements (Smith, 2015). Automated weed-control technologies are emerging as effective alternatives for efficient weed management (Westwood *et al*., 2018). In addition, decision support systems such as SELOMA, HERB, WEEDISM, GWM, PALEWEED and GESTINF assist farmers in herbicide selection and weed population forecasting. Advances in mechatronics, automation, GPS and DGPS technologies enable precise crop georeferencing and site-specific weed control. Furthermore, declining costs of unmanned aerial vehicles (UAVs) and improvements in sensor and camera technologies are expected to accelerate the adoption of aerial weed-monitoring and management systems in modern agriculture.

IT for Weed Management

Wearable technologies, contextualized learning, big data and augmented reality are emerging trends in Smart Weed Management (SWM). Wearable devices enable farmers to access real time information on soil conditions, moisture status, nutrient levels, environmental factors and crop-weed interactions directly in the field. The availability of affordable sensors has greatly expanded agricultural data collection through tools such as mobile devices, drones, cameras, RFID readers and wireless sensor networks. These technologies support data-driven and site-specific weed management decisions. In addition, optimization algorithms such as the Improved Weed Optimization Genetic Algorithm (IWOGA) have been used to improve the deployment and efficiency of RFID-based monitoring systems.

Carbon Credits obtained from Weed Management

SWM practices like alternate wetting and drying (AWD) and combined organic fertilizers reduce weed growth and lower GHG emissions, enabling rice growers to earn carbon credits. In the US 54.7 per cent of farmers are interested in selling carbon credits, 31.2 per cent unaware, 14.2 per cent opposed (Han & Niles 2023). Automatic steering with multispectral RGB cameras and proximal sensors supports large scale weed detection and monitoring. AI aids crop simulation and climate-smart modelling, improving carbon-credit processes (Gupta *et al.* 2022). Remote sensing and computer vision verify practices (cover cropping, tillage, N management) and quantify soil carbon sequestration. AI + sensor enabled SWM permits annual measurement and sale of credits, directly supporting sustainable farmers.

Alternate Wetting and Drying with Greenhouse Gas Reduction

Rising CO_2 and CH_4 drive global warming; flooded rice paddies produce 12 per cent of anthropogenic CH_4. Alternate wetting and drying (AWD) reduce CH_4 by 35 per cent and can cut yearly GHGs by 38 per cent while raising farmer profits by 6 per cent (Habib *et al*. 2023). AWD can lower weed biomass by suppressing lowland and broad-leaved weeds, though without proper weed management it may increase weed density (Gao *et al*. 2024; Enriquez *et al.* 2021). Farmers in SE Asia reported potential CH_4 reductions of 35 per cent with AWD (Yagi *et al.* 2020). AWD alternates draining and flooding during the season and saves 25-70 per cent water versus conventional rice systems. Given its GHG, water saving and weed management benefits, AWD qualifies as a smart weed management (SWM) approach and can help farmers earn carbon credits.

Integrated Use of Organic and Inorganic Fertilizers

The balanced use of organic and inorganic fertilizers can effectively reduce weed growth and methane (CH_4) emissions in rice-based systems (Hu *et al.,* 2024). Similarly, the application of concentrated organic manure before transplanting has been reported to suppress weed seed germination, thereby reducing weed density and dry matter accumulation (Ghosh *et al*., 2022). Chemically composed organic and inorganic fertilizers (COIF) have also shown no significant increase in greenhouse gas emissions compared to other organic fertilizer sources (Hu *et al*., 2024). Furthermore, modern sensing technologies can accurately assess soil nitrogen status and weather conditions, enabling precise fertilizer application. This sensor-based approach improves nutrient-use efficiency, reduces excessive fertilizer use, enhances crop productivity and contributes to effective weed management.

Harvest Weed Seed Control

Collecting and destroying weed seeds at harvest (e.g., via combine harvester modifications) reduces future weed infestations trials in Taastrup showed dry-weight reductions of 68.3 per cent, 40.8 per cent and 11.3 per cent for *Fallopia convolvulus*, *Sinapis arvensis* and *Stellaria media* (Ghosh *et al.* 2022). In soybean, seed capture at harvest lowered biomass and seed production of Amaranthus species. Passing chaff through high temperature exhaust (75-140°C for short intervals) during harvest markedly cut seed viability and subsequent weed emergence. Contaminated weed biomass can be safely disposed via biogas fermentation, helping control invasive species like *Heracleum mantegazzianum* and preventing soil return of *Avena fatua* seeds. AI (deep learning) improves seed shed and seedbank management by mapping weed locations, density and populations for SSWM (Rai *et al*. 2023). Remote sensing distinguishes weeds from crops by spectral signatures, enabling targeted management and patch mapping (Corceiro *et al*. 2023).

Organic Herbicides

Organic herbicides are weed control agents derived from natural sources such as plants, minerals or microbes and are used in organic farming and gardening (Hasan *et al.* 2021). Some common organic herbicides include acetic acid (vinegar) corn gluten meal and certain plant-based oils (Kumar and Kumar 2022). They can be an effective tool when used in conjunction with other weed control methods (Martelloni *et al.* 2020). Plants with bioherbicidal potential such as oregano, rosemary, thyme, mint and several other species in the *Lamiaceae* family are rich in essential oils (up to 8%) (De Mastro, El Mahdi and Ruta 2021). AI driven techniques like remote sensors for soil moisture prediction and autonomous robots for automating certain tasks reduce the reliance on synthetic herbicides. The spraying of organic herbicides in fields with the aid of drones and plant monitoring are no longer a burden for farmers (Talaviya *et al*. 2020).

Bioherbicides

Bioherbicides, which utilize plant pathogens for weed control, offer a targeted and environmentally friendly alternative to chemical herbicides with minimal adverse effects on non-target organisms (Hasan *et al*., 2021). Although numerous potential bioherbicidal agents have been identified, their widespread adoption is constrained by environmental factors such as temperature, humidity and rainfall as well as biological and technological limitations including host specificity, resistance development, short shelf life and application challenges (Hasan *et al*., 2021). In addition, regulatory and financial constraints often hinder their commercialization. Recent advances in artificial intelligence (AI) and remote sensing technologies have enhanced the effectiveness of bioherbicide based weed management by enabling accurate weed mapping and site-specific application strategies (Javaid *et al*., 2023). AI driven models can also predict weather conditions, monitor crop health and detect pest and disease outbreaks, thereby supporting the selection and timely application of suitable bioherbicides. The integration of AI with sensor technologies improves weed control efficiency while reducing risks to human health, soil quality, and the environment (Javaid *et al*., 2023).

Low Use of Herbicide Techniques

Integrated approaches such as IPM, IWM, mechanical and cultural tactics including minimal herbicide use reduce herbicide dependence. Herbicide banding with inter row cultivation in silage maize cuts chemical inputs while maintaining control. Droplet behaviour of glyphosate with silicone varies by weed species so nozzle choice and surfactant mix should be optimized. Early season SSWM mapping for wheat is preferred over blanket spraying to limit wild oat control inputs and pollution. Robotic systems like EcoRobotix's solar-powered sprayer detect weeds and use 90 per cent less herbicide than broadcast spraying (Raja *et al.* 2023). In-row vegetable spraying with precise AI computer vision achieves 98 per cent targeting accuracy robots could cut chemical use by 80 per cent and herbicide costs by 90 per cent (Swaminathan *et al*. 2023).

Improvement of Weed Competitive Ability of Crops

Breeding for weed-competitive crops remains a priority, but morphological trait selection has largely fallen short of breeders' expectations (Westwood *et al.* 2018). Plants detect neighbouring weeds early via light quality shifts, especially the red far-red ratio, informing competitive responses. Neonicotinoid seed treatments can enhance crop competitiveness under weed pressure. Weed identification is central to assessing crop weed competition. Deep learning models (VGG16, ResNet-101, AlexNet with graph convolutional networks) have been used for weed classification (Jiang *et al.* 2020). Semantic segmentation (e.g., FCN-8s) on synthetic hierarchical images helped analyse 8,000 images of ryegrass, clovers, soil and weeds.

CONCLUSION

Smart Weed Management (SWM) combines advanced technologies such as UAVs, sensors, robotics, artificial intelligence and precision application tools to improve weed control while reducing herbicide use, labour requirements, and production costs. By integrating these innovations with conventional weed management practices, SWM enhances efficiency, sustainability and resilience against challenges such as herbicide resistance and climate change. The adoption of supportive policies, regulatory incentives and continued technological advancements will be crucial for large scale implementation. Overall, the integration of conventional and smart approaches offers an effective, economical and environmentally sustainable pathway for future weed management.

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