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Integrated weed management in Black Gram (*Vigna mungo L.*): Recent advances, challenges, and future prospects

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Abstract

Black gram (Vigna mungo L.) is an important pulse crop cultivated extensively in Asia, particularly in India, owing to its high protein content and ability to improve soil fertility through biological nitrogen fixation. Despite its economic and nutritional significance, black gram productivity remains low due to several biotic and abiotic constraints, among which weed infestation is a major factor. Weeds compete with the crop for nutrients, moisture, light, and space, resulting in yield losses ranging from 30 to 80% depending on weed density, species composition, and duration of competition. Traditional weed control methods, such as manual weeding and intercultivation, are labor-intensive and often constrained by labor shortages and increased production costs. Consequently, integrated weed management (IWM) has emerged as a sustainable approach that combines cultural, mechanical, biological, and chemical weed control methods to achieve effective weed suppression while minimizing environmental impacts. Recent advances in weed management include the development of selective herbicides, precision agriculture technologies, remote sensing, drone-based weed detection, and decision-support systems for site-specific weed control. Cultural practices such as optimum sowing time, crop rotation, intercropping, competitive cultivars, and mulching have also contributed significantly to weed suppression. The integration of these approaches enhances weed control efficiency, improves crop productivity, and reduces dependence on herbicides. However, challenges such as herbicide resistance, changing weed flora due to climate change, environmental concerns, and the limited adoption of advanced technologies among smallholder farmers continue to hinder effective weed management.This review summarizes the current status of weed problems in black gram cultivation, evaluates recent advances in integrated weed management strategies, discusses major challenges, and highlights future research directions. Emphasis is placed on sustainable and environmentally friendly weed management approaches that can contribute to improved productivity and profitability of black gram cultivation under changing agricultural scenarios.

Keywords: Black gram, *Vigna mungo*, weed management, integrated weed management, herbicides, sustainable agriculture, pulse crops

Introduction

Black gram (*Vigna mungo* L. Hepper), commonly known as urd bean, is one of the most important pulse crops cultivated in tropical and subtropical regions, particularly in India, which contributes significantly to global pulse production and consumption (FAOSTAT, 2024). The crop is valued for its high protein content (20–25%), essential amino acids, minerals, and vitamins, making it an important source of dietary protein for millions of people (Graham & Vance, 2003) [14]. In addition to its nutritional significance, black gram improves soil fertility through biological nitrogen fixation and plays a vital role in sustainable cropping systems (Dakora & Keya, 1997) [8].Despite its importance, the productivity of black gram remains considerably lower than its genetic potential due to various biotic and abiotic constraints. Among these, weed infestation is recognized as one of the major yield-limiting factors in pulse production (Yaduraju *et al*., 2015) [36]. The slow initial growth rate and poor canopy development of black gram during the early stages of crop growth create favorable conditions for weed establishment and proliferation (Das, 2015) [9]. Weeds compete with the crop for nutrients, moisture, sunlight, and space, resulting in substantial reductions in growth and yield (Rao, 2000) [28]. Yield losses caused by uncontrolled weed growth in black gram have been reported to range from 30% to 80%, depending on weed density, species composition, and duration of competition (Yaduraju *et al*., 2015) [37].The critical period of crop–weed competition in black gram generally occurs between 20 and 45 days after sowing, during which effective weed control is essential to prevent significant yield losses (Singh *et al*., 2014) [30]. Common weeds associated with black gram cultivation include grasses such as *Echinochloa colona* and *Cynodon dactylon*, sedges such as *Cyperus rotundus*, and broad-leaved weeds including *Trianthema portulacastrum*, *Commelina benghalensis*, and *Amaranthus viridis* (Das, 2015) [9].Traditionally, weed management in black gram relies on manual weeding and intercultivation practices. Although these methods are effective, they are labor-intensive, costly, and often constrained by labor shortages during peak agricultural seasons (Rao, 2000) [28]. Herbicides provide efficient weed control and reduce labor requirements; however, their indiscriminate use may lead to environmental contamination, herbicide-resistant weed populations, and shifts in weed flora (Chhokar *et al*., 2012) [6].

Therefore, sustainable weed management approaches are increasingly needed to maintain productivity while minimizing ecological risks. Integrated Weed Management (IWM) has emerged as an effective and environmentally sustainable strategy that combines cultural, mechanical, biological, and chemical methods to suppress weed populations below economic threshold levels (Swanton & Murphy, 1996) [33]. Practices such as crop rotation, optimum sowing time, intercropping, competitive cultivars, mulching, and judicious herbicide use have shown considerable potential for improving weed control efficiency in pulse crops (Kumar *et al*., 2022) [20]. Furthermore, recent advances in precision agriculture, remote sensing, artificial intelligence, and drone-assisted weed detection offer new opportunities for site-specific and sustainable weed management (Mahajan *et al*., 2023) [22].Considering the growing challenges of labor scarcity, climate change, herbicide resistance, and the need for sustainable intensification of agriculture, effective weed management has become a critical component of black gram production systems. Therefore, this review aims to examine the current status of weed problems in black gram, evaluate recent advances in integrated weed management strategies, identify existing challenges, and discuss future prospects for sustainable weed control and enhanced crop productivity.

Recent Advances in Integrated Weed Management in Black Gram

Recent advances in weed management have transformed conventional weed control practices into more precise, efficient, and sustainable systems. In black gram (*Vigna mungo* L.), the integration of advanced technologies with traditional weed management approaches has improved weed control efficiency while reducing labor requirements and environmental impacts (Mahajan *et al*., 2023) [22]. These innovations are particularly important in the context of increasing labor scarcity, rising production costs, and concerns regarding herbicide resistance. One of the major advancements in weed management is the development of improved herbicide technologies. New generation herbicides such as imazethapyr, quizalofop-p-ethyl, propaquizafop, and fenoxaprop-p-ethyl provide selective and effective control of grassy and broad-leaved weeds in pulse crops (Yaduraju *et al*., 2015) [36]. Sequential and tank-mix herbicide applications have further enhanced weed control efficiency and broadened the spectrum of weed management while reducing the likelihood of herbicide resistance development (Chhokar *et al*., 2012) [6].Precision agriculture has emerged as a promising tool for site specific weed management. Technologies such as the Global Positioning System (GPS), Geographic Information Systems (GIS), and remote sensing facilitate accurate weed mapping and monitoring across agricultural fields (Mahajan *et al*., 2023) [22]. These technologies enable farmers to identify weed-infested areas and apply herbicides only where necessary, thereby reducing input costs and minimizing environmental contamination. Artificial intelligence (AI) and machine learning-based weed detection systems represent another significant advancement. Computer vision techniques can differentiate weeds from crop plants using digital images and sensor data, enabling real-time weed identification and targeted control measures (Westwood *et al*., 2018). Such technologies have the potential to improve weed management precision while reducing herbicide usage.

Drone assisted weed monitoring and herbicide application are increasingly being explored in modern agriculture. Unmanned aerial vehicles (UAVs) equipped with multispectral and hyperspectral sensors can rapidly detect weed infestations and assess weed density over large areas (Mahajan *et al*., 2023) [22]. Drone based spraying systems allow precise herbicide application, reducing labor requirements and improving application efficiency. The use of conservation agriculture practices has also gained importance in integrated weed management. Residue retention, reduced tillage, cover cropping, and mulching suppress weed emergence by limiting light penetration and creating physical barriers to weed growth (Chauhan *et al*., 2017) [5]. These practices contribute to improved soil health while reducing weed pressure. Recent research has highlighted the potential of biological weed management approaches, including the use of allelopathic crops, bioherbicides, and beneficial microorganisms. Plant derived allelochemicals and microbial bioagents can suppress weed germination and growth, offering environmentally friendly alternatives to synthetic herbicides (Duke *et al*., 2020) [11]. Although still in developmental stages, these approaches hold considerable promise for sustainable weed management in pulse production systems. Furthermore, climate smart weed management strategies are being developed to address the impacts of climate change on weed dynamics. Predictive models, decision-support systems, and integrated management frameworks are increasingly used to forecast weed emergence patterns and optimize weed control operations under changing environmental conditions (Korres *et al*., 2016) [19].Collectively, these advances demonstrate a shift from conventional weed control towards integrated, technology-driven, and environmentally sustainable weed management systems. The successful adoption of these innovations in black gram cultivation can enhance weed control efficiency, improve crop productivity, reduce production costs, and contribute to sustainable agricultural development (fig.1).

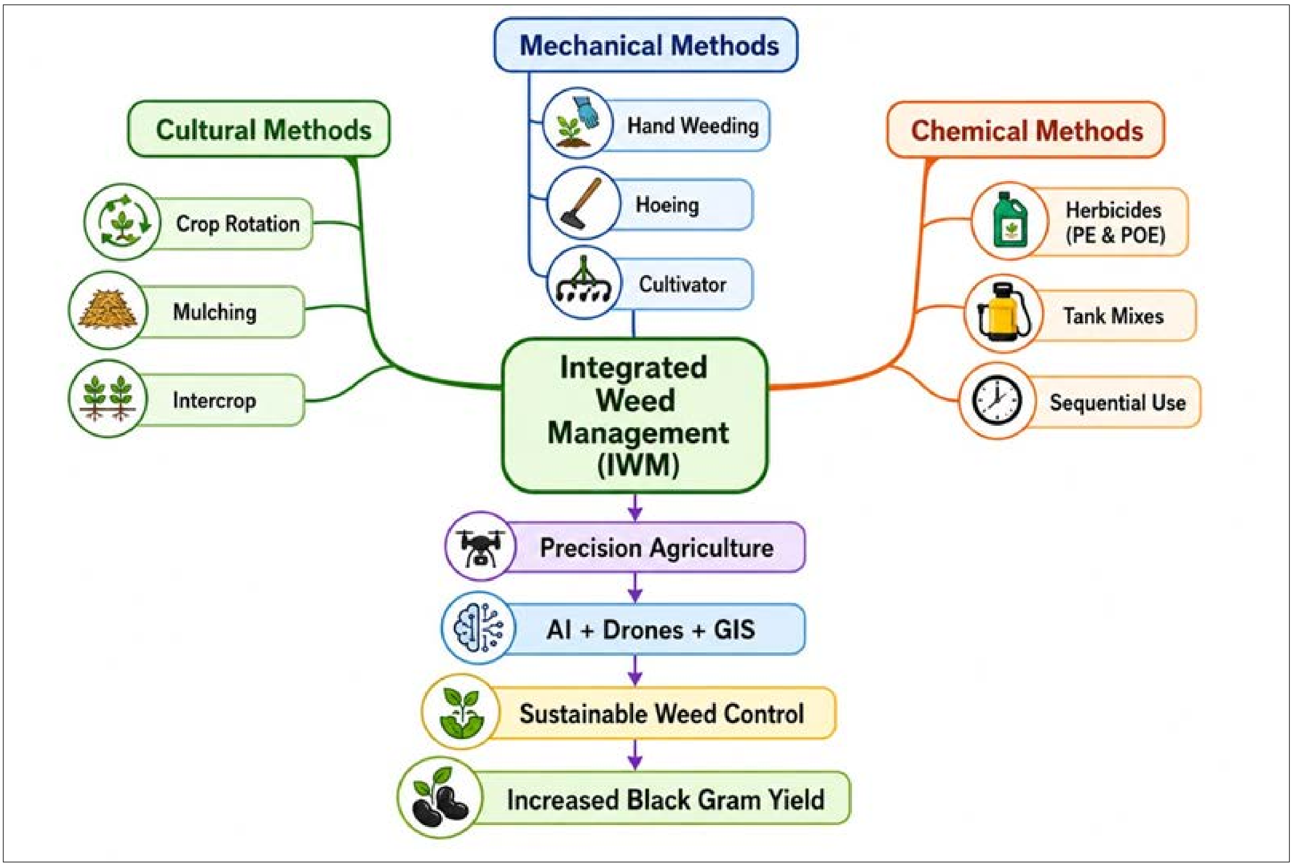

Fig 1: Integrated Weed Management Framework for Black Gram (Vigna mungo L.).The integration of cultural, mechanical, chemical, and precision agriculture approaches provides sustainable weed control and improved black gram productivity (Rao, 2000[28]; Swanton & Murphy, 1996; Yaduraju *et al*., 2015) [36]."

Weed Flora Associated with Black Gram Cultivation

The composition and distribution of weed flora in black gram fields vary considerably depending on agro-climatic conditions, soil type, cropping system, irrigation practices, and management strategies. Due to its slow initial growth and poor canopy development during the early growth stages, black gram is highly vulnerable to weed infestation. Weeds emerging simultaneously with the crop compete aggressively for nutrients, moisture, light, and space, thereby reducing crop growth and productivity (Rao, 2000; Das, 2015) [9, 28]. Weed flora associated with black gram cultivation can be broadly categorized into grasses, sedges, and broad leaved weeds as in **table 1**. Grassy weeds are often dominant under irrigated and rainfed conditions and include species such as *Echinochloa colona*, *Cynodon dactylon*, *Dactyloctenium aegyptium*, and *Digitaria sanguinalis*. These weeds exhibit rapid growth and high competitive ability, particularly during the early stages of crop establishment (Yaduraju *et al*., 2015) [36].Sedges constitute another important group of weeds in black gram fields. Among them, *Cyperus rotundus* is considered one of the world's most troublesome weeds due to its extensive underground tuber system and strong regenerative capacity. Other sedges, including *Cyperus iria* and *Fimbristylis miliacea*, may also occur depending on environmental conditions and cropping practices (Das, 2015) [9].

Broad leaved weeds are generally the most diverse group in black gram ecosystems. Common species include *Trianthema portulacastrum*, *Commelina benghalensis*, *Amaranthus viridis*, *Parthenium hysterophorus*, *Digera arvensis*, *Phyllanthus niruri*, *Celosia argentea*, and *Euphorbia hirta*. These weeds compete strongly for resources and may serve as alternate hosts for insect pests and plant pathogens, thereby indirectly affecting crop health and yield (Rao, 2000).The prevalence and intensity of weed infestation are influenced by seasonal conditions. During the kharif season, warm temperatures and adequate soil moisture favor rapid weed emergence and growth, resulting in severe crop weed competition. In irrigated systems, continuous moisture availability further enhances weed proliferation and necessitates effective weed management interventions (Yaduraju *et al* ., 2015) [37].Studies have reported that uncontrolled weed growth can cause yield losses ranging from 30% to 80% in black gram depending on weed density, species composition, and duration of competition (Singh *et al*., 2014) [30]. Therefore, understanding the weed flora associated with black gram cultivation is essential for developing effective and location-specific integrated weed management strategies. Accurate identification of dominant weed species facilitates the selection of appropriate cultural, mechanical, and chemical control measures, ultimately improving crop productivity and profitability (Chauhan, 2012; Rao, 2000) [3, 28].

Table 1: Common Weed Species, Their Common Names, and Image Reference Sources

S. No.	Scientific name	Common name	Suggested image source/reference	Image
1	*Amaranthus viridis*	Slender amaranth	CABI Invasive Species Compendium	
2	*Celosia argentea*	Silver cockscomb	Flora of India	
3	*Commelina benghalensis*	Benghal dayflower	CABI	
4	*Cynodon dactylon*	Scutch grass	USDA Plants Database	
5	*Cyperus iria*	Rice flatsedge	IRRI Weed Identification Guide	

6	*Cyperus rotundus*	Purple nutsedge	ICAR Weed Atlas	
7	*Dactylocteniu m aegyptium*	Crow foot grass	FAO Weed Identification Resources	
8	*Digera arvensis*	False amaranth	Flora of India	
9	*Digitaria sanguinalis*	Large crabgrass	USDA Plants Database	
10	*Echinochloa colona*	Jungle rice	IRRI Weed Guide	

11	*Euphorbia hirta*	Asthma plant	Flora of India	
12	*Fimbristylis miliacea*	Grass-like fimbry	IRRI Rice Weed Guide	

Critical Period of Crop Weed Competition in Black Gram (Vigna mungo L.)

The critical period of crop weed competition (CPWC) refers to the specific period during crop growth when weeds must be controlled to prevent unacceptable yield losses. In black gram, the crop exhibits slow initial growth and poor canopy development during the early stages, making it highly susceptible to weed competition. Therefore, timely weed management during the critical period is essential for achieving optimum crop growth and yield (Rao, 2000; Das, 2015) [9, 28].Several studies have reported that the critical period of crop–weed competition in black gram generally occurs between 20 and 45 days after sowing (DAS), although the exact duration may vary depending on environmental conditions, weed flora, crop variety, and management practices (Singh *et al.*, 2014; Yaduraju *et al.*, 2015) [30, 36]. During this period, weeds compete intensely with the crop for essential resources such as nutrients, water, light, and space as in **table 2** and **fig 2**. Uncontrolled weed growth during this stage can significantly reduce plant height, leaf area, dry matter accumulation, nodulation, and ultimately grain yield.Weeds emerging simultaneously with black gram are particularly harmful because they establish rapidly and utilize available resources before the crop develops an effective canopy. Broad-leaved weeds, grasses, and sedges present during the early vegetative stage can suppress crop growth and interfere with physiological processes such as photosynthesis and nitrogen fixation (Das, 2015) [9]. Yield losses due to unchecked weed competition in black gram have been reported to range from

30% to 80%, depending on weed density and duration of infestation (Yaduraju *et al.*, 2015) [37].Maintaining a weed-free environment during the first 20–45 DAS is therefore considered essential for maximizing crop productivity. Integrated weed management practices involving pre-emergence herbicides, timely hand weeding, intercultivation, mulching, and cultural methods are recommended to minimize weed competition during this critical period (Chhokar *et al.*, 2012) [6]. Effective weed control during the CPWC not only improves grain yield but also enhances nutrient-use efficiency, water-use efficiency, and overall crop health. Understanding the critical period of crop weed competition enables farmers and researchers to optimize weed management interventions and reduce unnecessary herbicide applications. Such knowledge forms the basis for developing efficient and economically viable integrated weed management strategies for sustainable black gram production.

Table 2: Effect of Weed Competition at Different Growth Stages of Black Gram

Growth Stage	Duration (DAS)	Impact of Weeds
Germination and Establishment	0–20	Moderate competition; crop establishment affected
Critical Period of Crop–Weed Competition	20–45	Severe competition for nutrients, water, light, and space
Flowering and Pod Formation	45–70	Reduced effect compared to early stages
Maturity	>70	Minimal effect on final yield

Adapted from Rao (2000), Das (2015), Singh *et al.* (2014), and Yaduraju *et al.* (2015) [9, 28, 30, 36].

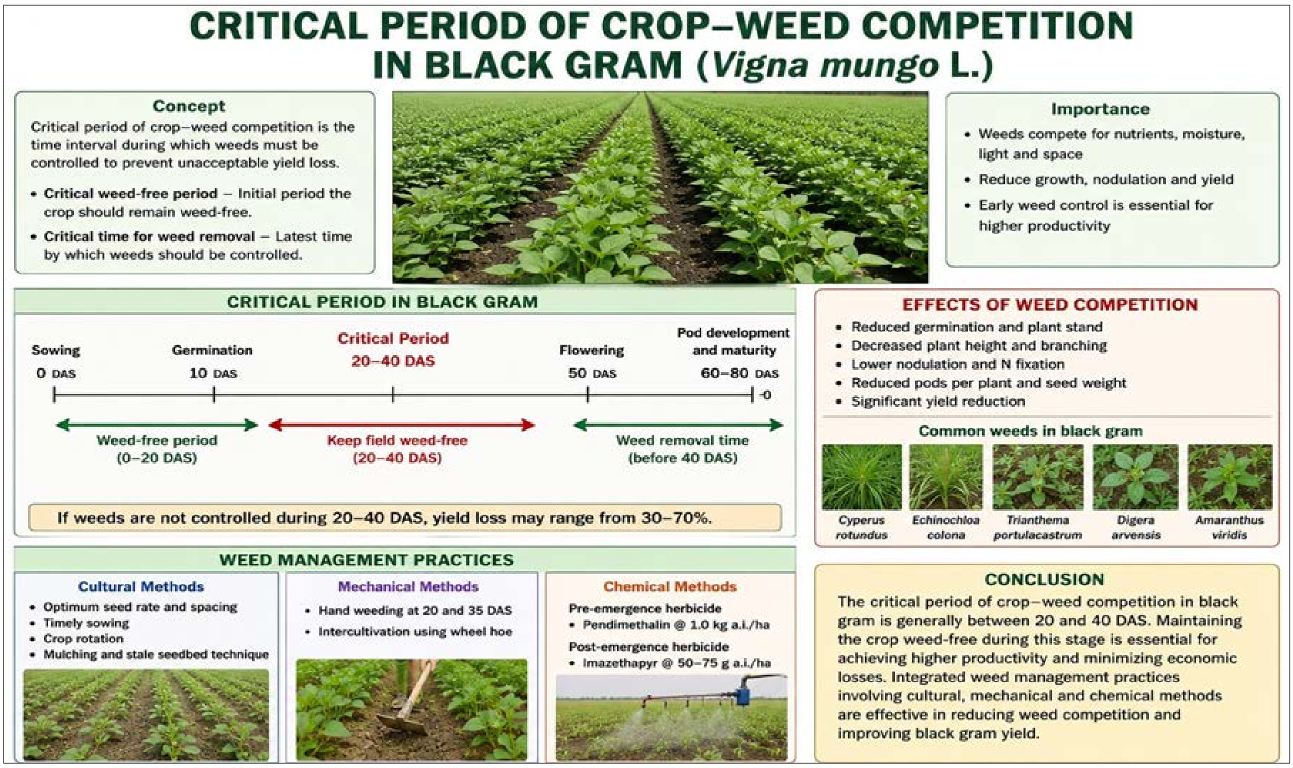

Fig 2: Critical Period of Crop –Weed Competition in Black Gram (Vigna mungo L.). Critical period of crop–weed competition in black gram (*Vigna mungo* L.) illustrating the weed-free period, major effects of weed competition, common weed species, and integrated weed management practices for minimizing yield loss.

1. Different method of Weed Management in Black Gram (*Vigna mungo* L.)

1.1 Cultural Methods of Weed Management in Black Gram (*Vigna mungo* L.)

Cultural weed management in black gram involves the adoption of suitable agronomic practices that promote vigorous crop growth and suppress weed infestation. The use of clean and certified seeds prevents the introduction of weed seeds into the field, while proper land preparation and tillage help in reducing existing weed populations by exposing weed seeds and vegetative propagules to unfavorable conditions (Rao, 2000) [28]. Timely sowing, maintaining optimum plant population through appropriate seed rate and spacing, and the use of competitive varieties improve crop Competitiveness against weeds by achieving early canopy closure (Yaduraju *et al*., 2015) [37]. Crop rotation and intercropping with suitable crops disrupt weed life cycles and reduce weed dominance in black gram fields (Rao, 2000) [28]. The adoption of stale seedbed techniques encourages weed seed germination before sowing and allows their removal, thereby reducing the weed seed bank (Chauhan & Johnson, 2010) [4]. Furthermore, mulching and proper nutrient and water management suppress weed emergence and enhance the crop's ability to compete for resources (Yaduraju *et al*., 2015) [37]. Therefore, cultural methods form an essential component of Integrated Weed Management (IWM), reducing reliance on herbicides and promoting sustainable black gram production (Rao, 2000) [28] reported in table 3 and fig 3,4.

Table 3: Major Cultural Weed Management Practices and Their Roles in Sustainable Weed Control

S. No.	Cultural method	Role in weed management	Reference
1	Clean and certified seeds	Prevents introduction and spread of weed seeds in the field	Rao (2000) [28]
2	Proper land preparation and tillage	Destroys existing weeds and exposes weed propagules to adverse conditions	Rao (2000) [28]
3	Timely sowing	Helps rapid crop establishment and improves crop competition with weeds	Yaduraju *et al.* (2015)
4	Optimum seed rate and spacing	Provides early canopy cover, reducing light available for weed growth	Yaduraju *et al.* (2015)
5	Crop rotation	Breaks the life cycle of problematic weeds and reduces weed build-up	Rao (2000) [28]
6	Competitive varieties	Vigorous crop growth suppresses weed emergence and growth	Yaduraju *et al.* (2015)
7	Intercropping	Provides better ground cover and reduces space for weeds	Rao (2000) [28]
8	Mulching	Suppresses weed emergence by blocking sunlight and conserving moisture	Yaduraju *et al.* (2015)
9	Stale seedbed technique	Encourages weed germination before sowing and allows their removal, reducing the soil weed seed bank	Chauhan & Johnson (2010) [4]
10	Balanced nutrient and water management	Enhances crop vigour and increases competitiveness against weeds	Yaduraju *et al.* (2015)

Fig 3: Different weed management approaches in crop production: (A) plastic mulch used for weed suppression and moisture conservation, (B) conservation agriculture field with crop residue mulch reducing weed emergence, and (C) manual hand weeding operation carried out in a row crop field.

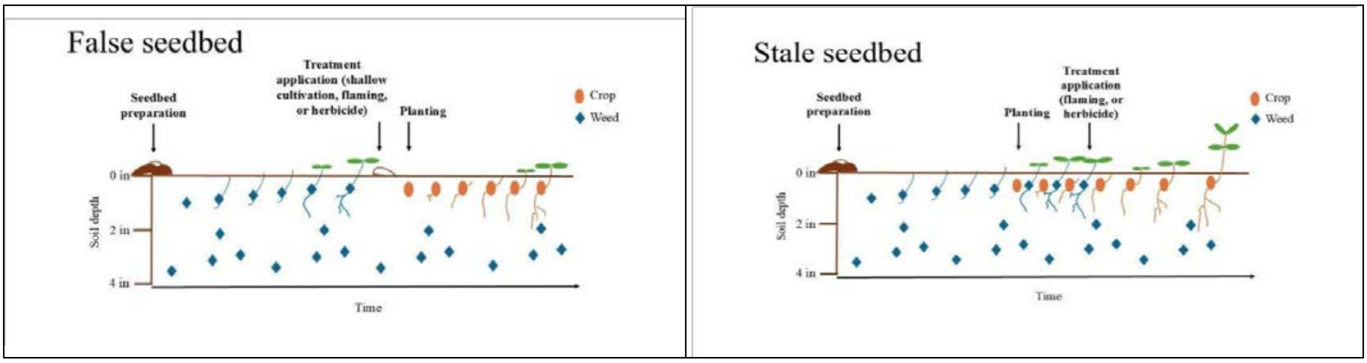

Fig 4: Comparison of false seedbed and stale seedbed techniques for weed management. In the false seedbed method, weeds are allowed to germinate after seedbed preparation and are destroyed before crop planting through shallow cultivation, flaming, or herbicide application. In the stale seedbed method, the crop is planted after initial weed emergence, and weeds are controlled selectively using herbicides or other treatments to reduce weed competition during crop establishment. This Cultural methods of weed management in black gram (*Vigna mungo* L.) (Adapted from Food and Agriculture Organization (FAO), Indian Council of Agricultural Research (ICAR), ICAR-Indian Institute of Pulses Research (IIPR) and International Rice Research Institute (IRRI) resources).

1.2 Biological Methods of Weed Management in Black Gram (*Vigna mungo* L.)

Biological weed management in black gram (*Vigna mungo* L.) involves the use of living organisms such as insects, plant pathogens, grazing animals, and competitive plants to suppress weed Growth and reduce weed populations observed in table 4. Although biological control is less commonly practiced in black gram compared to cultural and chemical methods, it can be integrated as a component of Integrated Weed Management (IWM) to achieve sustainable weed control (Rao, 2000; Yaduraju *et al.*, 2015) [28, 38].

Table 4: Major Biological Weed Management Practices and Their Roles in Sustainable Weed Control

S. No.	Biological agent	Target weed	Mode of action	Reference
1	*Zygogramma bicolorata* (leaf-feeding beetle)	*Parthenium hysterophorus* (Parthenium weed)	Adults and larvae feed on leaves, reducing weed growth and seed production	Rao Dhileepa (2001) (2000); n
2	*Cyrtobagous salviniae* (weevil)	*Salvinia molesta* (Salvinia)	Feeds on buds and leaves causing damage and suppression of the weed	Julien (2002) *et al.*
3	*Puccinia spegazzinii* (rust fungus)	*Mikania micrantha*	Causes disease and reduces the vigour and spread of the weed	Ellison (2008) *et al.*
4	Competitive cover crops/green manure plants	Various weeds	Suppress weeds by competition for light, water, nutrients, and space	Yaduraju *et al.* (2015)

1.3 Mechanical Weed Management in Black Gram (*Vigna mungo* L.)

Mechanical weed management involves the physical removal or destruction of weeds using manual labour, hand tools, or mechanical implements in table 5. It is one of the oldest and most effective methods of weed control and forms an important component of Integrated Weed Management (IWM) (Rao, 2000) [28]**.** Common mechanical methods include hand weeding, hoeing, intercultivation, tillage, mowing, and the use of mechanical weeders. Hand weeding removes weeds directly from the field, while Hoeing and intercultivation disturb the soil and uproot young weeds between crop rows (Yaduraju *et al.*, 2015) [37]**.** Tillage operations reduce weed populations by burying weed seeds and exposing underground propagules to adverse environmental conditions. Mowing and cutting prevent weed flowering and seed production, thereby reducing weed spread (Chauhan, 2012) [2]**.** Mechanical methods are environmentally safe, reduce dependence on herbicides, and improve soil aeration; however, they require higher labour input and are less effective against deeply rooted perennial weeds (Rao, 2000; Yaduraju *et al.*, 2015) [28, 38]**.**

Table 5: Major Mechanical Weed Management Practices and Their Roles in Sustainable Weed Control

S. No.	Mechanical method	Description	Purpose/Effect	Reference
1	Hand weeding	Manual removal of weeds by hand	Eliminates weeds along with roots and reduces crop competition	Rao (2000) [28]; Yaduraju *et al.* (2015) [36]
2	Hoeing	Use of hand hoes, wheel hoes, or rotary hoes	Uproots weeds and improves soil aeration	Rao Yaduraju (2015) (2000); *et al.*
3	Intercultivation	Soil stirring between crop rows using implements	Controls young weeds and conserves soil moisture	Yaduraju (2015) [36] *et al.*
4	Tillage	Primary and secondary tillage operations	Buries weed seeds and destroys underground plant parts	Rao (2000) [28]; Chauhan (2012) [2]
5	Mowing and cutting	Cutting weeds before flowering and seed set	Prevents weed propagation and seed dispersal	Chauhan (2012) [2]
6	Mechanical weeders	Use of power weeders, rotary weeders, and cultivators	Enables quick and efficient weed control over larger areas	Yaduraju *et al.* (2015) [36]

1.4 Recent Chemical Methods of Weed Management in Black Gram (*Vigna mungo* L.)

Chemical weed management in black gram involves the judicious use of herbicides to control weeds during the critical

Crop weed competition period (15–45 days after sowing) in table 6. Recent approaches emphasize the use of pre-emergence (PE) and post-emergence (PoE) herbicides, either alone or integrated with other weed management practices, to achieve effective and economical weed control.

Table 6: Major Chemical Weed Management Practices and Their Roles in Sustainable Weed Control

S. No.	Chemical method	Herbicide and dose	Time of application	Purpose/Effect	Reference
1	Pre-emergen ce herbicide	Pendimethalin 30 EC @ 0.75–1.0 kg a.i. ha ^{1}	1–3 DAS	Controls annual grasses and broad-leaved weeds	Rao (2000); Yaduraju *et al.* (2015) [28, 38]
–				by inhibiting seedling emergence	
2	Pre-emergen ce herbicide	Pendimethalin + Imazethapyr (ready-mix) @ 800–1000 g ha^{-1}	0–3 DAS	Provides broad-spectrum control of grasses, sedges, and broad-leaved weeds	Choudhary *et al.* (2018)
3	Early post-emerge nce herbicide	Imazethapyr 10 SL @ 50–75 g a.i. ha^{-1}	15–20 DAS	Controls emerged weeds, especially broad-leaved weeds and some grasses	Yadav *et al.* (2017)
4	Post-emerge nce herbicide	Imazamox + Imazethapyr @ 60–70 g a.i. ha^{-1}	15–20 DAS	Effective against mixed weed flora and provides prolonged weed suppression	Sharma *et al.* (2019)
5	Post-emerge nce herbicide	Quizalofop-p-ethyl 5 EC @ 50 g a.i. ha ^{1}	15–20 DAS	Selectively controls grassy weeds in black gram	Rao (2000) [28]; Kumar *et al.* (2020)
6	Sequential herbicide application	Pendimethalin^{-} (PE) followed by Imazethapyr (PoE)	PE followed by 15–20 DAS	Improves weed control efficiency, increases yield, and reduces weed competition	Patel *et al.* (2021)

1.5 Precision Agriculture in Weed Management of Black Gram (*Vigna mungo* L.)

Precision agriculture in weed management involves the use of advanced technologies such as Global Positioning System (GPS), Geographic Information System (GIS), remote sensing.

Drones, artificial intelligence (AI), and sensor-based technologies to detect, monitor, and manage weeds accurately showed table 7. In black gram, precision weed management helps reduce herbicide use, lower production costs, and minimize environmental impacts while maintaining crop productivity.

Table 7: Major Precision Weed Management Approaches in Black Gram

S. No.	Precision method	Description	Purpose/Benefits	Reference
1	GPS and GIS-based weed mapping	Mapping the distribution and density of weeds within fields	Helps identify weed hotspots and enables site-specific management	Blackshaw *et al.* (2008) [1]; Zhang *et al.* (2002)
2	Remote sensing	Use of satellite or aerial images to detect weed infestation based on spectral differences	Enables early detection and monitoring of weed populations	Mulla (2013) [23]; Huang *et al.* (2018)
3	Drone (UAV)-based weed detection	Unmanned aerial vehicles equipped with RGB or multispectral cameras identify weed patches	Provides real-time weed surveillance and precise decision-making	Peña *et al.* (2013)
4	AI and machine learning	Image-processing algorithms distinguish weeds from crop plants	Supports automated weed identification and targeted control	Slaughter *et al.* (2008) [31]; Hasan *et al.* (2021)
5	Sensor-based herbicide application	Optical sensors detect weeds and activate nozzles only where weeds are present	Reduces herbicide consumption and environmental contamination	Young *et al.* (2014)
6	Variable-rate herbicide technology (VRT)	Applies different herbicide doses according to weed density and distribution	Improves herbicide efficiency and reduces unnecessary application	Stafford (2000) [32]; Zhang *et al.* (2002)
7	Robotic and autonomous weeding	Use of robots for mechanical or spot weed removal	Reduces labour requirement and increases precision	Fennimore al. (2016) et

1.6 Herbicide Resistance: An Emerging Challenge in Black Gram Weed Management

Herbicide resistance has become one of the most significant challenges in modern weed management systems worldwide. Herbicide resistance is defined as the inherited ability of a weed biotype to survive and reproduce following exposure to a herbicide dose that would normally be lethal to the wild-type population (Heap, 2024) [16]. Continuous and repeated use of herbicides with the same mode of action exerts selection pressure on weed populations, leading to the evolution of resistant biotypes (Powles & Yu, 2010) [27].In black gram cultivation, herbicides such as pendimethalin, imazethapyr, quizalofop-p-ethyl, and propaquizafop are commonly used for weed control. Although these herbicides effectively manage a wide range of weeds, excessive dependence on a limited number of herbicide groups may accelerate the development of herbicide-resistant weed populations (Chhokar *et al*., 2012) [6]. Resistant weeds can survive herbicide applications, multiply rapidly, and eventually dominate the weed flora, reducing the effectiveness of existing weed management programs.The mechanisms of herbicide resistance are broadly categorized into target-site resistance and non-target-site resistance. Target-site resistance occurs when genetic mutations alter the herbicide-binding site, preventing effective herbicide action. Non-target-site resistance involves mechanisms such as reduced herbicide absorption, limited translocation, enhanced metabolism, or sequestration of herbicides within plant tissues (Powles & Yu, 2010) [27]. These mechanisms enable weeds to survive herbicide treatments and reproduce successfully.

The consequences of herbicide resistance include increased weed management costs, reduced crop productivity, greater reliance on higher herbicide doses, environmental concerns, and limited availability of effective control options (Norsworthy *et al*., 2012) [24]. Furthermore, resistant weed populations may lead to shifts in weed flora, where difficult-to-control species become dominant in agricultural ecosystems.Integrated Weed Management (IWM) is considered the most effective strategy for delaying and managing herbicide resistance. Practices such as herbicide rotation, herbicide mixtures with different modes of action, crop rotation, intercropping, mulching, hand weeding, and mechanical cultivation reduce selection pressure on weed populations and help maintain herbicide effectiveness (Norsworthy *et al*., 2012) [24]. The integration of cultural, mechanical, biological, and chemical approaches is therefore essential for sustainable weed management in black gram.Recent advances in precision agriculture, remote sensing, and artificial intelligence-based weed detection systems also offer opportunities for site-specific herbicide application, reducing unnecessary herbicide use and lowering the risk of resistance development (Westwood *et al*., 2018). Future weed management strategies should emphasize resistance monitoring, diversified weed control practices, and farmer awareness programs to ensure long-term sustainability of black gram production systems.

Future Prospects of Integrated Weed Management (IWM) in Black Gram

The future of Integrated Weed Management (IWM) in black gram (*Vigna mungo* L.) lies in the adoption of advanced, sustainable, and eco-friendly technologies to improve weed control efficiency while reducing reliance on chemical herbicides. The integration of precision agriculture tools such as drones, remote sensing, artificial intelligence (AI), and site-specific weed management will enable early weed detection and precise application of control measures, thereby reducing input costs and environmental impacts.The development and adoption of climate-resilient and competitive black gram varieties, along with improved crop rotation, cover cropping, mulching, and conservation agriculture practices, will strengthen natural weed suppression. Greater utilization of biological control agents, bioherbicides, and allelopathic crops has the potential to provide environmentally safer alternatives for managing problematic weeds.Future research should focus on understanding weed ecology, monitoring herbicide resistance, and developing integrated strategies that combine cultural, mechanical, biological, and chemical methods according to local weed flora and agro-climatic conditions. The use of decision-support systems, digital farming platforms, and farmer-centered extension programmes will further enhance the adoption of IWM practices.Overall, the future of IWM in black gram depends on the successful integration of modern technologies with traditional weed management practices to achieve higher productivity, improved profitability, reduced environmental risks, and long-term sustainability of black gram production.

Conclusion

Integrated Weed Management (IWM) has emerged as a sustainable and effective approach for managing weed problems in black gram (*Vigna mungo* L.) cultivation. The integration of cultural, mechanical, biological, and chemical weed control methods provides better weed suppression, reduces crop–weed competition, and enhances growth, yield, and profitability of black gram. Recent advances such as precision agriculture, drone-assisted herbicide application, remote sensing, artificial intelligence (AI)-based weed detection, improved herbicide formulations, and the development of bio-herbicides have opened new opportunities for efficient and environmentally safe weed management.However, the adoption of IWM faces several challenges, including diverse weed flora, emergence of herbicide-resistant weeds, limited availability of suitable bio-control agents, high initial cost of advanced technologies, and lack of awareness among farmers. Addressing these constraints requires continuous research, farmer education, and the development of location-specific weed management strategies.Future weed management in black gram should focus on integrating modern technologies with traditional practices such as crop rotation, optimum sowing methods, competitive cultivars, mulching, and timely mechanical and chemical interventions. A holistic and eco-friendly IWM approach will be essential to improve black gram productivity, conserve natural resources, reduce environmental risks, and ensure sustainable pulse production under changing climatic conditions.

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