



# AGRI MAGAZINE

(International E-Magazine for Agricultural Articles)

Volume: 03, Issue: 06 (June, 2026)

Available online at <http://www.agrimagazine.in>

© Agri Magazine, ISSN: 3048-8656

## Integrated Pest Management (IPM): A Sustainable Approach for Modern Agriculture with Stress Indices for Arid and Semi-Arid Areas

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Integrated Pest Management (IPM) is a science-based approach that uses multiple pest control strategies in a coordinated manner to keep pest populations below economically harmful levels while minimizing risks to human health, the environment, and non-target organisms. This article examines how IPM can be made more effective in arid and semi-arid agricultural regions by integrating quantitative stress indices, namely the Aridity Index (AI), Temperature Stress Index (TSI), Soil Moisture Stress Index (SMSI), Normalized Difference Vegetation Index (NDVI), and Water Deficit Index (WDI). The paper discusses the six components of IPM, the challenges specific to dryland farming, the role of botanical pesticides and traditional knowledge, and a practical implementation framework. It is concluded that combining IPM with stress-index-based decision tools can significantly improve pest management outcomes for smallholder and dryland farmers across India and similar agro-climatic regions.

**Keywords:** Integrated Pest Management (IPM), Arid and Semi-Arid Agriculture, Stress Indices, Sustainable Pest Management, Climate-Smart Agriculture.

### Introduction

Globally, crop losses due to pest damage are estimated at 20–40% of total agricultural production annually. In India, this figure is particularly significant given that more than 60% of agricultural land is rainfed, and arid and semi-arid zones cover large parts of Rajasthan, Gujarat, Maharashtra, Haryana, and parts of Uttar Pradesh. In such regions, climate-driven stress not only reduces crop productivity directly but also makes crops more vulnerable to pest attack by weakening their natural defence mechanisms. Conventional pesticide-based pest control, while effective in the short term, has led to serious problems including development of pest resistance, destruction of beneficial natural enemies, pesticide residues in food and water, and increased input costs for farmers. Against this background, Integrated Pest Management (IPM) has emerged as the most rational, sustainable alternative. The Food and Agriculture Organization of the United Nations (FAO) defines IPM as 'the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment' (FAO, 2022).

Integrated Pest Management (IPM) has evolved as a comprehensive pest management strategy that integrates biological, cultural, mechanical, and chemical methods to maintain pest populations below economically damaging levels while minimizing environmental risks.

According to Kogan (1998) and Ehler (2006), IPM represents a dynamic and knowledge-intensive approach that emphasizes ecological balance and sustainable crop protection. A further challenge in dryland pest management is the lack of reliable, real-time data to guide decision-making. Stress indices derived from agro-meteorological and remote sensing data offer a cost-effective, science-based solution to this problem. In practical farming situations, such information can support timely and informed pest management decisions. By quantifying the degree of environmental stress experienced by a crop, these indices allow extension workers and farmers to anticipate pest outbreak windows and take preventive action before damage occurs. This article reviews IPM components, their applicability in arid and semi-arid zones, and the use of five key stress indices as decision-support tools.

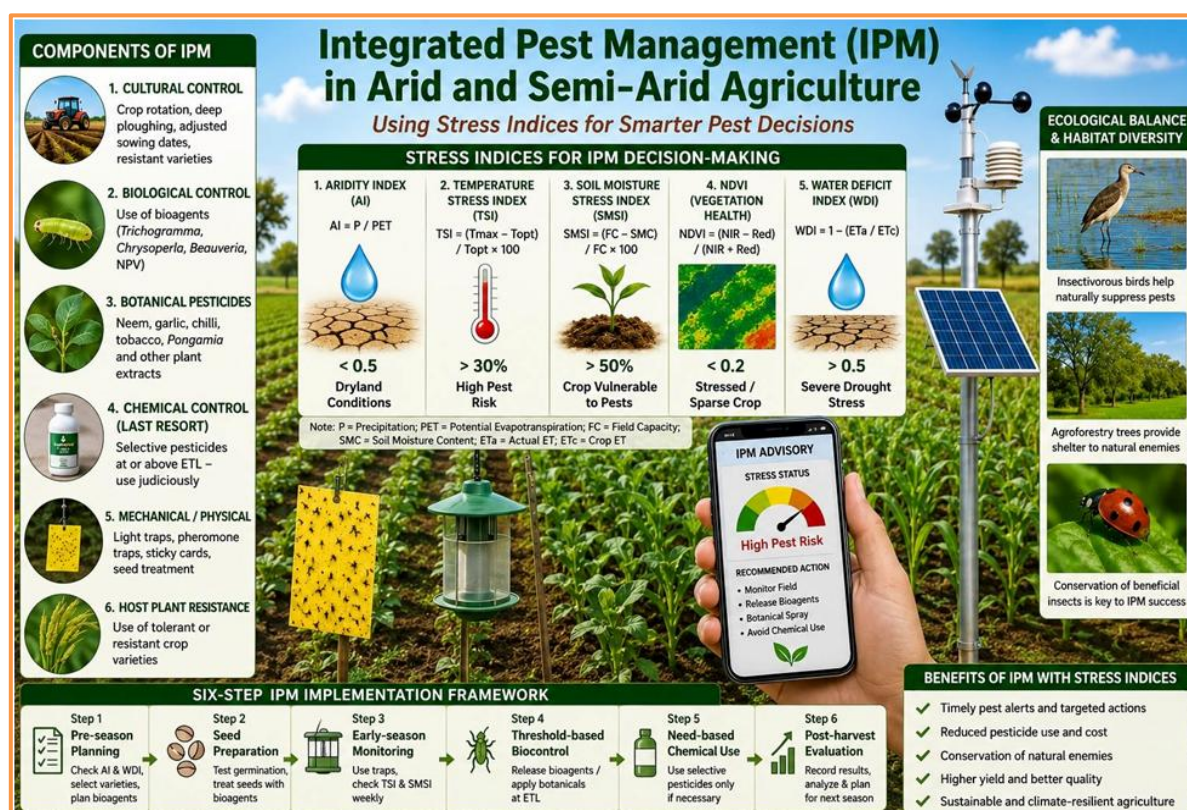


Figure 1. Conceptual representation of stress-index-based Integrated Pest Management (IPM) in dryland farming systems.

## Components of Integrated Pest Management

IPM is a multi-component system. No single strategy is adequate on its own; rather, the combination of complementary methods is what makes IPM effective and durable.

**Cultural Control:** Cultural practices form the first line of defence in IPM. These include crop rotation (which breaks the pest life cycle by denying pests a continuous host), deep ploughing before sowing (which exposes soil-dwelling pupae and larvae to solar heat and predators), adjustment of sowing dates to escape peak pest pressure, and intercropping with non-host or repellent species. Timely seed germination testing before sowing is also an important preparatory step, as a uniform crop stand reduces stress and pest entry points in the field. This is particularly important under rainfed and dryland conditions.

**Biological Control:** Biological control involves the deliberate use of natural enemies to suppress pest populations. Key bioagents used in Indian dryland agriculture include: *Trichogramma chilonis* (egg parasitoid of lepidopteran pests), *Chrysoperla carnea* (predatory green lacewing), *Beauveria bassiana* (entomopathogenic fungus effective against whiteflies and thrips), and Nuclear Polyhedrosis Virus (NPV) against *Helicoverpa armigera*. These bioagents are commercially available, low-cost, and safe for humans and the environment. Their effectiveness is greatest when pest populations are at or below the Economic Threshold

Level (ETL). However, field performance may vary depending on climatic conditions and pest pressure.

**Botanical Pesticides and Traditional Knowledge:** India possesses a remarkable repository of plant-based pest control knowledge. Nadkarni (2000) documented over 200 plant species with verified pesticidal properties in Indian traditional medicine systems. Among these, neem (*Azadirachta indica*) is the most widely researched and commercially used. Azadirachtin, the active compound in neem, disrupts insect moulting hormones and acts as an antifeedant against more than 200 insect species without harming natural enemies or pollinators. The growing interest in botanical pesticides reflects the need for environmentally safe pest management options. Isman (2006) highlighted that plant-derived insecticides, repellents, and deterrents can serve as effective alternatives to synthetic pesticides while reducing ecological and human health concerns. Other effective botanical preparations include garlic (*Allium sativum*) extract, tobacco (*Nicotiana tabacum*) decoction, chilli (*Capsicum annuum*) spray, and *Pongamia pinnata* seed extract. These preparations are particularly suitable for resource-poor smallholder farmers in arid zones because the raw materials are locally available at low or no cost.

**Chemical Control:** In IPM, synthetic chemical pesticides are used strictly as a last resort, and only when pest populations cross the ETL. The choice of chemical must favour selective, short-residue insecticides that spare natural enemies. Botanical acaricides are preferred over synthetic chemicals for mite management in dryland crops such as okra, groundnut, and brinjal. Application should be done during early morning or late evening hours to reduce chemical breakdown in high temperatures and to protect pollinators active during daytime (Dhaliwal and Arora, 2016). Excessive reliance on synthetic pesticides has resulted in considerable environmental and economic costs. Pimentel (2005) reported that pesticide misuse can adversely affect biodiversity, water quality, and human health, further strengthening the need for sustainable pest management approaches such as IPM.

**Mechanical and Physical Control:** Pheromone traps, light traps, yellow sticky traps, and seed treatment with bioagents are important non-chemical tools in the IPM toolkit. In arid zones with low relative humidity, light traps are particularly effective for monitoring and mass trapping of moth pests such as *Spodoptera frugiperda* and *Helicoverpa armigera*. Regular monitoring using these tools provides early warning of pest build-up, allowing timely and targeted interventions.

**Table 1. Components of IPM and Their Applicability in Arid and Semi-Arid Farming Systems**

IPM Component	Key Practices	Suitable for Dryland?	Main Benefit
Cultural Control	Crop rotation, deep ploughing, adjusted sowing dates, resistant varieties	Yes low input cost	Disrupts pest life cycle
Biological Control	<i>Trichogramma spp.</i> , <i>Chrysoperla carnea</i> , <i>Beauveria bassiana</i> , NPV	Yes with heat-tolerant bioagents	Eco-friendly, self-sustaining
Botanical Pesticides	Neem ( <i>Azadirachta indica</i> ), garlic, <i>Pongamia pinnata</i> extracts	Highly suitable plants locally available	Safe, residue-free pest knock-down
Chemical Control (last resort)	Selective synthetic pesticides at or above Economic Threshold Level (ETL)	Use cautiously avoid soil residue	Quick suppression of heavy infestations
Mechanical/Physical	Light traps, pheromone traps, sticky cards, seed treatment	Highly effective in low-humidity zones	Non-chemical, targeted pest monitoring
Host Plant Resistance	Tolerant or resistant cultivar selection	Best option for arid zones	Long-term, cost-effective suppression

Source: Compiled from Dhaliwal and Arora (2016); Nadkarni (2000); FAO (2022)

## Stress Indices as Decision-Support Tools for IPM

The integration of quantitative stress indices into IPM planning offers a way to move from reactive to predictive pest management. When crops are physiologically stressed due to heat or drought, they emit stress-related volatile compounds, accumulate simple sugars, and reduce secondary metabolite production all of which make them more attractive and less resistant to pest attack. Measuring stress indices allows farmers and extension workers to anticipate these windows of vulnerability.

### 1. Aridity Index (AI)

The Aridity Index, defined as  $AI = P/PET$  (where  $P$  = mean annual precipitation and  $PET$  = potential evapotranspiration), was developed by the United Nations Environment Programme (UNEP). Regions with  $AI < 0.2$  are classified as hyperarid, 0.2–0.5 as arid, and 0.5–0.65 as semi-arid (Spinoni et al., 2015). In IPM terms, the AI guides the choice of drought-tolerant crop varieties with inherent pest resistance, and helps predict seasons with high sucking pest pressure.

### 2. Temperature Stress Index (TSI)

$TSI = (T_{max} - T_{opt}) / T_{opt} \times 100$ , where  $T_{max}$  is the maximum ambient temperature and  $T_{opt}$  is the optimum temperature for crop growth. A TSI value above 30% signals significant thermal stress that coincides with explosive population growth of thermophilic pests such as spider mites (*Tetranychus urticae*) and whiteflies (*Bemisia tabaci*). This index helps schedule early morning spray operations and prioritize biocontrol release on high-TSI days.

### 3. Soil Moisture Stress Index (SMSI)

$SMSI = (FC - SMC) / FC \times 100$ , where  $FC$  is field capacity and  $SMC$  is the actual soil moisture content. A value above 50% indicates severe drought stress during which crops become susceptible to both above-ground sucking pests and below-ground nematodes and soil pathogens. Linking SMSI values to automated pest alert messages (via SMS-based agro-advisory systems) can enable timely biocontrol interventions.

### 4. Normalized Difference Vegetation Index (NDVI)

$NDVI = (NIR - Red) / (NIR + Red)$ , where  $NIR$  = near-infrared reflectance and  $Red$  = red-band reflectance of the canopy. Derived from satellite sensors such as Sentinel-2 and Resourcesat-2, NDVI values below 0.2 indicate sparse or severely stressed vegetation that is likely to face heightened pest pressure. At the district level, NDVI maps can identify pest hotspot areas for targeted scouting campaigns.

### 5. Water Deficit Index (WDI)

$WDI = 1 - (ET_a / ET_c)$ , where  $ET_a$  is actual evapotranspiration and  $ET_c$  is potential crop evapotranspiration. WDI values above 0.5 indicate severe crop water stress and historically coincide with outbreaks of aphids, thrips, and mites in dryland crops such as pearl millet (*Pennisetum glaucum*), chickpea (*Cicer arietinum*), and sorghum (*Sorghum bicolor*). Integrating WDI forecasts with pest monitoring data can significantly reduce unnecessary pesticide applications.

**Table 2. Stress Indices Used in IPM Decision-Making for Arid and Semi-Arid Regions**

Stress Index	Formula	Critical Threshold	IPM Application
Aridity Index (AI)	$AI = P / PET$	$< 0.5$ = dryland conditions	Crop variety and bioagent selection
Temperature Stress Index (TSI)	$TSI = (T_{max} - T_{opt}) / T_{opt} \times 100$	$> 30\%$ = high pest risk	Adjust spray timing to cooler hours
Soil Moisture Stress Index (SMSI)	$SMSI = (FC - SMC) / FC \times 100$	$> 50\%$ = crop vulnerable to pests	Irrigation-linked pest alert trigger
NDVI (Vegetation Health)	$NDVI = (NIR - Red) / (NIR + Red)$	$< 0.2$ = stressed/sparse crop	Satellite pest hotspot identification
Water Deficit Index (WDI)	$WDI = 1 - (ET_a / ET_c)$	$> 0.5$ = severe drought stress	Predict aphid/thrips outbreak windows

Note:  $P$  = Precipitation;  $PET$  = Potential Evapotranspiration;  $FC$  = Field Capacity;  $SMC$  = Soil Moisture Content;  $ET_a$  = Actual ET;  $ET_c$  = Crop ET

## Ecological Balance and Habitat Diversity in IPM

A critical but often neglected dimension of IPM is the role of ecological diversity in sustaining natural pest regulation. Insectivorous birds, particularly winter migratory species, are important natural pest regulators in agricultural landscapes. Research on habitat utilization by winter migrants at Kolleru Lake, Andhra Pradesh one of India's largest freshwater lakes and a Ramsar Wetland Site has documented the use of surrounding paddy and vegetable fields by species such as Pheasant-tailed Jacana and various herons as feeding grounds, where insects form a major part of their diet. Conservation of such habitats within and around agroforestry systems can meaningfully support biological pest suppression. Agroforestry systems common in semi-arid India incorporating trees such as *Prosopis cineraria*, *Acacia senegal*, *Ziziphus mauritiana*, and *Azadirachta indica* serve as ecological corridors and refugia for beneficial insects including parasitoids, predatory beetles, and spiders. Maintaining tree cover within or around crop fields, even at low density, has been shown to increase the diversity and abundance of natural enemies of crop pests.

**Table 3. Estimated Contribution of IPM Components to Overall Pest Suppression (%) in Dryland Cropping Systems**

IPM Component	Contribution to Overall Pest Suppression (%)
Biological Control	30
Cultural Control	25
Chemical Control (Judicious Use)	15
Host Plant Resistance	15
Mechanical and Physical Methods	10
Regulatory Measures	05

Source: Based on expert synthesis from Dhaliwal and Arora (2016); FAO (2022); ICAR (2020)

## IPM Implementation Framework for Arid and Semi-Arid Regions

Effective IPM implementation in dryland agriculture requires a phased, season-linked approach aligned with stress index thresholds. The following six-step framework is proposed.

**Step 1 — Pre-season planning:** Calculate the Aridity Index and Water Deficit Index for the zone. Select drought-tolerant, pest-resistant cultivars. Arrange bioagents and botanical pesticide raw materials in advance.

**Step 2 — Seed preparation:** Conduct seed germination testing as recommended to ensure uniform crop stand. Treat seeds with *Trichoderma viride* or *Beauveria bassiana* to protect against soil-borne pests.

**Step 3 — Early-season monitoring:** Install pheromone traps (1 per 0.5 ha) and yellow sticky traps at crop canopy level from the first week after germination. Check TSI and SMSI weekly during peak summer months.

**Step 4 — Threshold-based biocontrol:** When pest counts approach 50% of the ETL, release *Trichogramma* cards (50,000 eggs/ha) or apply *Beauveria bassiana* ( $1 \times 10^8$  conidia/ml) as a preventive spray. Use NDVI data to prioritize high-risk plots.

**Step 5 — Chemical intervention (if needed):** Apply botanical acaricides (neem oil at 3% or garlic extract at 5%) when pest population crosses ETL. Resort to selective synthetic insecticides only when botanical preparations prove insufficient.

**Step 6 — Post-harvest assessment:** Deep plough the field to destroy pest pupae in the soil. Record pest incidence, crop yield, input costs, and spray schedule in a farm diary for adaptive management in the next season.

## Conclusions

Integrated Pest Management is the most scientifically rational and economically viable approach to crop protection in modern agriculture, particularly in resource-limited, climate-stressed dryland farming systems. This review demonstrates that the effectiveness of IPM can be significantly enhanced in arid and semi-arid areas by incorporating quantitative environmental stress indices namely the Aridity Index, Temperature Stress Index, Soil

Moisture Stress Index, NDVI, and Water Deficit Index as early warning and decision-support tools. Biological control and cultural practices should form the backbone of any dryland IPM programme, supplemented by locally available botanical pesticides rooted in traditional knowledge as validated by Nadkarni (2000) and others. Mechanical monitoring tools such as pheromone and light traps provide cost-effective, chemical-free early warning systems ideally suited to low-income farming communities.

At the policy level, Krishi Vigyan Kendras (KVKs), State Agricultural Universities, and extension departments must take the lead in translating stress-index-based IPM advisories into farmer-friendly, regional-language communication. Investment in weather-monitoring infrastructure, satellite data access, and farmer training in digital agro-advisory tools will be essential to scale up this framework across India's vast dryland agricultural belt. With these inputs in place, IPM can genuinely become the foundation of a pest-free, cost-efficient, and ecologically sound agriculture for millions of smallholder farmers. However, successful implementation ultimately depends on farmer awareness, local environmental conditions, and timely decision-making. Integrated Pest Management also contributes significantly to the sustainable intensification of agriculture. Pretty and Bharucha (2015) reported that IPM practices can improve crop productivity while reducing pesticide dependence, thereby promoting environmental sustainability and long-term agricultural resilience.

### Future Perspectives

Further field-based studies are required to validate stress-index-based pest forecasting under different agro-climatic conditions of India.

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