Plant growth regulators (PGRs) further complement cultivation management by regulating physiological and biochemical processes associated with vegetative growth and flowering. Gibberellic acid (GA_3) enhances stem elongation, cell division, and flower initiation, while improving branching and flower size. Research has shown that the application of GA_3 at 200 ppm combined with pinching at 14 days after transplanting provides the most favourable combination for promoting early flowering and improving flower production (Isnawati et al., 2023).

Efficient irrigation scheduling has also become an important component of precision marigold production. Irrigation based on Class A pan evaporation (0.75 Epan) improves water-use efficiency by supplying water according to crop demand while minimizing unnecessary water losses. Such precision irrigation systems enhance nutrient uptake, maintain favourable soil moisture, and improve flower yield and economic returns compared with conventional flood irrigation (Chitra et al., 2025).

Recent advances in artificial lighting have further expanded opportunities for controlled-environment production. Light quality regulates photosynthesis, chlorophyll synthesis, photomorphogenesis, and carotenoid biosynthesis through phytochrome- and cryptochrome-mediated signalling pathways. The combined use of red and blue LED lights has been reported to promote balanced vegetative growth, improve pigment accumulation, and enhance flower quality, whereas red light alone significantly increases lutein concentration. These findings demonstrate that manipulating light spectra offers an effective strategy for improving production efficiency, shortening crop duration, and increasing both ornamental and industrial value under protected cultivation systems.

3.9 Advances in nutrient management

Integrated nutrient management has become an essential component of sustainable marigold production. The combined application of biofertilizers such as *Azotobacter*, phosphate-solubilizing bacteria (PSB), *Azospirillum*, and arbuscular mycorrhizal fungi with reduced rates of chemical fertilizers improves nutrient availability, root growth, flower yield, and nutrient-use efficiency (Abdulsada et al., 2013). Seedling root dipping in biofertilizer slurry before transplanting enhances early root colonization and nutrient uptake, while integration with farmyard manure or vermicompost further improves soil microbial activity, nutrient cycling, and long-term soil fertility.

3.10 Integrated pest and disease management

Integrated Pest and Disease Management (IPDM) has evolved from reliance on frequent chemical pesticide applications to environmentally sustainable management strategies that combine cultural, biological, mechanical, and chemical approaches. Modern IPDM programmes emphasize preventive management, conservation of beneficial organisms, and judicious pesticide use to minimize environmental impacts while maintaining effective pest suppression.

Recent studies comparing different pest management modules have demonstrated that adaptable IPDM systems integrating neem cake, vermicompost, biological control agents, and selective pesticides effectively reduce populations of thrips, mites, and bud borers (*Helicoverpa armigera*) while lowering pesticide dependence (Nikita et al., 2026). Such integrated approaches improve crop health by maintaining ecological balance and reducing the likelihood of pesticide resistance development.

Advances in molecular breeding have further strengthened pest and disease management through the identification of quantitative trait loci (QTLs) and marker-assisted selection (MAS) for resistance against important diseases such as powdery mildew and nematodes. The integration of resistant cultivars with biological control and precision crop management provides a more sustainable approach than reliance on chemical control alone.

In addition to its ornamental value, marigold also functions as an effective trap crop in vegetable production systems. According to Parihar et al. (2025), marigold attracts several insect pests and suppresses nematode populations when intercropped with solanaceous crops such as tomato and potato, thereby reducing pest pressure on the main crop. This multifunctional role enhances biodiversity, supports integrated crop protection strategies, and contributes to environmentally sustainable agricultural production.