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False Smut Disease an emerging thread of Rice productivity in Manipur

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Introduction

Rice is of the Gramineae or Poaceae grass family, scientifically known as *Oryza sativa*. The carbohydrates rich major cereal crop is the most remarkable around the globe which prefers warm climates during the warm summer months. Manipur is closely intertwined with the history of rice cultivation, which served as a pivotal factor in shaping subsistence, social organization and political authority. The main staple food of the state is rice in fact, 100% of the population consume rice for their sustenance. The state has 0.18 million ha under rice cultivation, which covers both irrigated and rainfed areas. 90% of gross cropped area (GCA) of the state is under paddy cultivation (Singha and Mishra, 2015). More than 80% of the total population in Manipur are engaged in agriculture and allied sectors (Roy *et al*, 2018). However, farmers are still facing various constraints during cultivation of rice crop in Manipur (Thangjam and Jha, 2020). Thus, rice research has to be geared up to develop strategies for alleviating losses due to pests and diseases. One such disease is the rice false smut (RFS) disease that threat to yield and grain quality. Reduction of constraints caused by pest and disease infestation in rice cultivation can achieve food security and socio-economic development.

False smut of rice can cause rice yield losses ranging from 3 to 70 % depending on weather conditions and rice cultivars (Baite *et al*. 2021). False smut was first reported in Arkansas in 1997 and is now likely widespread where rice is grown. False smut directly impacts grain yield and quality by partially or completely replacing rice kernels with fungal spore masses. This substitution disrupts normal grain development, leading to significant reductions in both quantity and quality of a harvest. However, the false smut fungus produces two types of mycotoxins, ustiloxins and ustilaginoidins (Wang *et al*. 2019b). Both mycotoxins are carcinogenic and pose a threat to human and animal health through the consumption of contaminated rice grains and straw. However, for the past five to six years, false smut of rice, also known as *kambongsatpi* in local language, has been emerging as an important disease affecting rice-grain production. The disease has been increasing in an alarming proportion widely in the eastern and north-eastern part of India. Among the farmers, the disease has been considered as an omen of good harvest as it appears to be more prevalent in seasons favourable for good growth and high yield. But they must be aware of the threat due to vigorously increasing disease incidence. Understanding the extent of the disease and development of proper management strategies is the need of the time.

Disease Symptoms and Epidemiology

Usually, the disease is sporadic in the field and also in an individual ear, only a few grains are affected. However, in severe cases, many smut balls may aggregate together (Singh, 1990). If infection occurs before fertilization, most of the glumes remain sterile without any visible sign of infection. Typical large, velvetty, green smut balls (pseudomorphs) develop when infection occurs after fertilization (Kulkarni and Moniz, 1975). False smut symptoms are readily visible outside of rice kernels, as opposed to kernel smut, where symptoms are generally only visible during harvest or at late maturity stage. *Ustilaginoidea virens* infects rice plants during panicle development. The signs and symptoms of false smut become visible generally two to three weeks after flowering. False smut is characterized by the replacement of rice kernels by globose, velvety spore balls with powdery chlamydospores (Schneider and Groth 2018; Sun *et al*. 2020). Immature smut balls are orangish yellow (Fig 1), whereas mature smut balls turn to greenish black (Fig 2). The false smut fungus infects rice flowers and replaces the inner organs with fungal mycelia (Tanaka *et al* 2008; Tang *et al* 2008). The false smut fungus produces two different overwintering structures, chlamydospores at the asexual stage and sclerotia at the sexual stage. Sclerotia can maintain a high rate of germination for up to 5 years, enabling long-term infection in the field (Yong *et al* 2018). Both chlamydospores and sclerotia can produce conidia upon germination, which can be the primary source of inoculum.

Fig 1. Progressing to yellow-orange

Fig 2. Maturing to greenish-black

Disease Cycle

The false smut pathogen survives in both rice seed and soil via sclerotia and chlamydospores. Sclerotia, a high-density fungal hyphae mass that is produced at the sexual stage, can remain dormant for several years (Yong *et al*., 2018). They also overwinter on collateral host/ alternate hosts on many grasses and wild rice. These spores served as primary inoculums. The infection time is an important factor in determining the loss. If it occurs in early stage of flower opening, the ovary is destroyed and the loss is high whereas if the infection is in the later stage, then the grains set and the mycelium invades the endosperm and produces mass of spores. The disease is favored by rainfall accompanied by cloudy days during the period between flowering and maturity of the grain with RH > 90% and temperature 25-35^{0}C. The climatic condition of Manipur is highly suitable for the development of the disease. Therefore, it has been becoming one of the most important diseases of major concerned.

Management Strategies

Proper management strategies must be taken up against the disease. Successful control of kernel smut and false smut relies on employing management strategies to reduce damage to an acceptable level. In Arkansas, cultivars with documented resistance to false smut are limited, with the bulk of the current rice cultivars being on the order of moderately susceptible, or very susceptible phenotypes (Hardke *et al* 2024). However, unlike other rice diseases, kernel smut and false smut are difficult to control using individual management strategies because of an incomplete understanding of their in-season disease infection process and the lack of effective management tools. The disease infection process and the impact of weather conditions and plant growth stage on disease development are not well understood. No scouting methods are available to detect and predict the development of false smut during the cropping season because the symptoms and signs of the disease are observed only at or shortly before maturity. Rice cultivars with acceptable levels of resistance are not commercially available. Therefore, an integrated management approach should include avoiding late planting, the excessive application of pre-flood nitrogen fertilizer and preventative fungicide applications in fields with a history of disease or where cultivars with known susceptibility to false smut are planted.

Conclusion

False smut of rice is known to occur in almost all the rice growing areas in the world. At present, there is a need to understand the importance of this disease and develop all the necessary precautionary measures to prevent yield loss. Although losses due to plant diseases may be reduced by the use of disease resistance cultivars, crop rotation or sanitation practices, fungicides are often essential to maximize crop yields. The development and use of resistant cultivars is the most effective and economical approach to minimize the damage caused by kernel smut and false smut and maximize production returns. Unfortunately, no cultivars or genotype sources with high levels of resistance have been identified so far. Recent progress in genomics studies has provided some understanding of the pathogenicity and infection mechanisms of false smut fungi. However, more research is needed to better understand the mechanism and genetics of resistance in rice, virulence in the pathogens, and the impacts of surrounding environments on pathogen–host interactions. On the other hand, Fungicides play important role in improving food quality and they also contribute to food safety by controlling many fungi that produce mycotoxins such as aflotoxins, ergot toxins, fusarium toxins, patulin and tenuazonic acid (Knight *et al* 1997). However, to maintain their effectiveness and to minimize their effect on human health and on the environment, they should be used in a rational and informed way. Hence, there is a need to develop more resistant varieties against the disease. Researchers must focus on released of new resistant local varieties that will serve as a boon for the farmers. If the disease is not checked right now, it may take the shape of an epidemic in few years.

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Thrips as a Challenge in Vegetable Production: Biology, Damage and Integrated Management

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Introduction

Vegetables are an important component of the human diet and play a vital role in nutrition, food security and economic development. They are major sources of vitamins, minerals, dietary fibre, antioxidants and other bioactive compounds. Vegetable crops also provide farmers with higher economic returns within a short duration and contribute to the development of agriculture-based industries. India is the second-largest vegetable-producing country in the world after China and contributes approximately 15% of global vegetable production. The country produces more than 219 million metric tonnes of vegetables annually; however, productivity is adversely affected by insect pests and diseases (Kumar and Pal, 2020).

Thrips (Order: Thysanoptera) are minute and economically important insect pests that cause damage to vegetables, fruits, oilseeds, pulses and ornamental plants worldwide. They cause direct damage by sucking sap from leaves, buds, flowers and fruits, resulting in leaf curling, deformation, flower and fruit shedding, and reduced plant growth. In addition, several thrips species act as vectors of plant viruses, further increasing their economic importance (Mound and Kibby, 1998; Rao *et al*., 2018).

In India, the incidence of thrips is increasing rapidly in major vegetable crops such as chilli, tomato, brinjal, onion, garlic, okra, cucumber, bitter gourd, bottle gourd, pumpkin, watermelon, muskmelon and beans. Among these, *Scirtothrips dorsalis*, *Thrips palmi*, *Thrips tabaci*, *Frankliniella occidentalis* and the recently emerging species *Thrips parvispinus* are important damaging species. *Thrips parvispinus* has emerged as a highly destructive pest of chilli and other crops, and under favourable conditions, yield losses may reach 80-100% (Sridhar *et al*., 2021; Prasannakumar *et al*., 2021).

Climate change, crop diversification, expansion of protected cultivation and indiscriminate use of insecticides are making the thrips problem increasingly serious. Thrips infestation may cause 30-100% yield loss in different vegetable crops, thereby affecting production, quality and farmers' income. Therefore, knowledge of thrips identification, biology, host plants, damage symptoms and integrated pest management strategies is essential (Mouden *et al*., 2017; Jensen, 2000; Bielza, 2008).). Such information can contribute significantly to increasing vegetable production and quality while promoting environmentally safe, sustainable and profitable agricultural systems.

Major Identification Characteristics of Thrips

Thrips are very small, slender and elongated insects, generally measuring 1-2 mm in length. Their body colour may vary from yellow and light to dark brown or black. They possess piercing and sucking-type mouthparts, and their antennae generally consist of 6-9 segments. Adults have two pairs of narrow, membranous wings fringed with long hairs along the margins, which constitute one of their characteristic identification features. Nymphs are wingless and generally light yellow or cream in colour. Adult thrips move rapidly and often remain hidden in leaves, buds and flowers. The presence of a silvery or silvery-white sheen and minute black fecal spots on affected plant parts are also characteristic signs of thrips infestation.

Life Cycle

The life cycle of thrips generally consists of the egg, two nymphal stages, prepupal, pupal and adult stages. Female thrips lay their eggs within tender leaves, buds, flowers or other soft plant tissues. Nymphs hatch from eggs within 2-7 days and feed on plant sap as they grow. The nymphal stages are followed by the prepupal and pupal stages, which are generally completed in the soil, dried leaves or protected portions of plants. Adults subsequently emerge from the pupal stage. Under favourable temperature and humidity conditions, the complete life cycle of thrips may be completed within approximately 12-20 days, allowing their populations to increase rapidly (Mouden *et al*., 2017).

Damage Symptoms

Thrips damage plants by sucking sap from tender leaves, buds, flowers and fruits. Both nymphs and adults are damaging stages. Their feeding causes a silvery appearance on affected leaves, along with upward curling, crinkling and deformation of the leaves. Under severe infestation, plant growth becomes stunted, and plants appear weak. Infestation of flowers may result in flower shedding and adversely affect fruit formation. Rough, brown or cork-like lesions may develop on mature fruits, reducing their quality and market value. Consequently, considerable yield losses may occur. In addition, some thrips species act as vectors of plant viruses, causing both direct and indirect damage to crops (Rao *et al*., 2018).

(a) Thrips on flower (b) Adult thrips (c) Symptoms of thrips damage on chilli

Integrated Pest Management of Thrips in Vegetable Crops

Considering the polyphagous nature, high reproductive potential, short life cycle and developing insecticide resistance in thrips, effective management cannot rely solely on chemical control. Therefore, the following integrated pest management (IPM) strategies can be adopted for successful and long-term management of thrips.

Cultural Measures

- Use healthy and pest-free planting material.
- Keep fields free from weeds and crop residues, as several weeds may serve as alternative hosts for thrips.
- Adopt balanced fertilizer management and avoid excessive application of nitrogenous fertilizers.
- Follow crop rotation to disrupt the life cycle of the pest.

Mechanical and Physical Measures

- Install blue or yellow sticky traps at 20-25 traps per hectare for monitoring and partial suppression of thrips populations.
- Remove and destroy infested leaves, buds and other affected plant parts.
- In protected cultivation, insect-proof nets can be used to prevent the entry of thrips.

Biological Control

- Conserve natural enemies such as ladybird beetles, *Chrysoperla* and predatory mites.
- Entomopathogenic biopesticides such as *Beauveria bassiana*, *Metarhizium anisopliae* and *Verticillium lecanii* may be applied at 4.0 g or 1 ml per litre of water.
- Neem-based products at 1500-10,000 ppm may be effective when applied during the early stages of infestation.

Chemical Control

- Before sowing, seeds may be treated with imidacloprid 70 WS @ 12 g per kg seed, and at the time of transplanting, carbofuran 3G @ 33 kg per hectare or phorate 10G @ 10 kg per hectare may be applied to the soil.
- Continuous use of insecticides belonging to the same chemical group should be avoided to prevent the development of insecticide resistance. Therefore, insecticides such as spinosad, spinetoram, fipronil or other locally recommended insecticides should be rotated appropriately.
- During spraying, the lower surface of leaves and flowers should be thoroughly covered because thrips often hide in these locations.
- Once the economic threshold level is exceeded, one of the following insecticides may be applied at the recommended dose.

Insecticide	**Dose**
Imidacloprid 17.8% SL	3.0 ml/10 L water
Dimethoate 30% EC	1.0 ml/L water
Fipronil 5% SC	1.5 ml/L water
Emamectin benzoate 5% SG	4 g/10 L water

Insecticide	Dose
Spinosad 45% SC	3.2 ml/10 L water
Thiacloprid 21.7% SC	6.0 ml/10 L water
Abamectin 1.9% EC	5.0 ml/10 L water
Spinetoram 11.7% SC	5.0 ml/10 L water
Cyantraniliprole 10.26% OD	6.0 ml/10 L water
Spirotetramat 15.31% OD	5.0 ml/10 L water
Oxydemeton-methyl 25% EC	1.0 ml/L water
Phosalone 35% EC	2.0 ml/L water

Monitoring and decision-based management

- Regularly inspect the crop and initiate management measures as soon as the initial occurrence of thrips is detected.
- Monitor thrips populations using sticky traps and plant samples.
- Chemical control should be undertaken only when the pest population reaches or exceeds the economic threshold level and based on the severity of infestation.

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Heterosis Breeding in Cucurbitaceous Vegetable Crops

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Abstract

Cucurbitaceous vegetables constitute an important group of horticultural crops that includes cucumber, bitter gourd, bottle gourd, ridge gourd, sponge gourd, pumpkin, squash, muskmelon and watermelon. Many cucurbits possess biological features that make hybrid breeding particularly attractive, including monoecious or gynoecious sex expression, relatively easy manipulation of pollination, abundant pollen, seed production and substantial exploitable variation for yield, earliness and fruit quality. Heterosis, or hybrid vigour, refers to the superior performance of an F_1 hybrid over its parents. In cucurbitaceous crops, heterosis has been exploited for increasing fruit yield, number of fruits, fruit size, earliness, quality and in some cases, tolerance to biotic and abiotic stresses (Yu et al., 2021). Combining ability analysis, particularly general combining ability (GCA) and specific combining ability (SCA), assists breeders in identifying suitable parents and promising cross combinations (Griffing, 1956). Recent advances in molecular markers, genomics and prediction of hybrid performance are creating opportunities to make heterosis breeding more efficient. This review summarizes the genetic basis, breeding approaches, crop-wise utilization, advantages, constraints and future prospects of heterosis breeding in cucurbitaceous vegetable crops.

Keywords: *Cucurbitaceae; heterosis; hybrid vigour; F_1 hybrids; combining ability; GCA; SCA; hybrid breeding; vegetable crops*

1. Introduction

Cucurbitaceous vegetables are economically important crops cultivated in tropical, subtropical and temperate regions and include cucumber, muskmelon, watermelon, bitter gourd, bottle gourd, ridge gourd, sponge gourd, pumpkin and squash. Their fruits are widely consumed fresh, cooked, processed and pickled, while several species also possess nutritional and medicinal value. Improvement in productivity and quality can be achieved through selection, hybridization, recurrent selection and heterosis breeding. Among these approaches, hybrid breeding is particularly effective because genetically diverse parents can produce F_1 hybrids with superior performance for important traits. In cucumber, heterosis has been reported for earliness, fruit number, fruit length, fruit weight and total fruit yield, demonstrating its potential for commercial hybrid development (Ene et al., 2019; Kumari et al., 2021). The reproductive biology of cucurbits further facilitates hybrid seed production, as monoecious plants possess distinct male and female flowers, while gynoecious lines predominantly produce female flowers. These characteristics make controlled pollination and hybridization comparatively convenient. Moreover, the production of numerous seeds per fruit can support efficient multiplication of hybrid seed. Thus, the combination of favourable reproductive biology and strong heterosis for yield and associated traits has established cucurbits as important crops for the development and utilization of commercial F_1 hybrids.

2. Concept and Genetic Basis of Heterosis

Heterosis, commonly termed hybrid vigour, is the phenomenon in which an F_1 hybrid exhibits greater performance than its parents for one or more traits. The comparison may be made with the mid-parent value, the better parent or a commercial standard. Accordingly, relative heterosis, heterobeltiosis and standard heterosis are commonly estimated in breeding experiments. The genetic basis of heterosis is complex. Dominance, overdominance and epistatic interactions have traditionally been proposed to explain hybrid superiority. The dominance hypothesis attributes hybrid vigour to the masking of deleterious recessive alleles by favourable dominant alleles from the other parent, whereas the overdominance hypothesis proposes that heterozygosity itself can provide an advantage at particular loci. Epistasis emphasizes interactions among genes at different loci (Chen, 2013).

3. Estimation of Heterosis

For a cross between parents P1 and P2 with F_1 performance F, relative heterosis can be expressed as:

Relative heterosis (%) = $[(F - MP) / MP] \times 100$, where MP is the mid-parent value, calculated as $(P1 + P2)/2$.

Heterobeltiosis (%) = $[(F - BP) / BP] \times 100$, where BP is the better parent.

Standard heterosis (%) = $[(F - SC) / SC] \times 100$, where SC represents the standard or commercial check.

For traits in which lower values are desirable, such as days to flowering or days to marketable maturity, negative heterosis can be advantageous.

4. Importance of Combining Ability in Hybrid Breeding

Heterosis studies are often complemented by combining ability analysis. General combining ability reflects the average performance of a parent in hybrid combinations and is commonly associated with additive genetic effects, whereas specific combining ability reflects the performance of particular cross combinations beyond what would be predicted from parental GCA and is commonly associated with non-additive genetic effects, including dominance and epistasis (Griffing, 1956). When SCA variance is greater than GCA variance, non-additive effects may have an important role in determining the trait and hybrid breeding can be particularly useful. Diallel, line × tester and related mating designs are frequently used to evaluate GCA and SCA; the statistical basis for diallel analysis was formalized by Griffing (1956) and Hayman (1954) and these frameworks remain the standard approach in cucurbit breeding studies. Combining ability information helps breeders identify diverse parents, avoid unproductive crosses and select combinations with high yield potential, desirable fruit attributes and suitable adaptation.

5. Heterosis in Major Cucurbitaceous Vegetable Crops

5.1 Cucumber

Cucumber is one of the most important cucurbitaceous crops for heterosis breeding. Commercial hybrid development has benefited from gynoecious lines, which produce predominantly female flowers and can reduce the labour needed for hybrid seed production (Jat et al., 2015). Heterosis has been reported for earliness, number of female flowers, fruit number, fruit length, fruit weight and total fruit yield, with significant GCA and SCA variances typically observed for most yield-related traits (Ene et al., 2019). Hybrid breeding is also important for parthenocarpic cucumber production, particularly under protected cultivation where fruit set and quality must remain stable under specific environmental conditions. The magnitude of heterosis reported for cucumber varies considerably between studies and germplasm sets; while some diallel studies report substantial hybrid vigour for yield. More recent work using introgression of indigenous and exotic sources has demonstrated that residual heterosis for earliness and yield traits can be recovered in advanced generations, broadening the options available for cucumber hybrid development (Kumari et al., 2021). The molecular and genetic resources available in cucumber have expanded substantially, and marker-assisted approaches are increasingly used to track sex-expression traits and to help identify parents with complementary alleles for hybrid combinations.

5.2 Bitter Gourd

Bitter gourd is a highly valued cucurbitaceous vegetable because of its distinctive fruit, nutritional composition and medicinal importance. Heterosis breeding has been widely investigated for fruit yield and its components and hybrids may show superiority for number of fruits per plant, fruit weight, fruit length, earliness and overall yield (Mallikarjunarao et al., 2020). Heterosis has also been examined for quality and biochemical traits; recent diallel work has extended combining-ability and heterosis analysis to biochemical and nutritional attributes, indicating that hybrid breeding in bitter gourd is not limited to yield improvement but can also contribute to nutritional quality improvement (Saini et al., 2026). The crop's sex expression and cross-pollination behaviour provide practical opportunities for controlled hybrid seed production.

5.3 Bottle Gourd

Bottle gourd is another important cucurbit in which heterosis has been exploited for yield and earliness. Important target traits include days to first female flower, number of fruits per plant, fruit weight, fruit length and total yield, with several line × tester and diallel studies reporting substantial standard heterosis for fruit yield (Masud et al., 2021). Recent studies have also demonstrated heterosis for nutritional quality traits such as dry matter content, ascorbic acid, reducing sugars and total soluble solids, highlighting the potential of hybrid breeding to combine productivity gains with improved nutrient content (Bhatt et al., 2023).

5.4 Ridge Gourd and Sponge Gourd

Ridge gourd and sponge gourd have considerable diversity in fruit shape, size, fibre characteristics, earliness and yield. Heterosis breeding can combine desirable attributes from diverse parental lines and may provide gains for fruit number, fruit weight, total yield and mineral content; line × tester studies in ridge gourd have reported significant heterosis together with a predominance of non-additive gene action for most yield-related and quality traits (Singh et al., 2017). Compared with cucumber and bitter gourd, systematic hybrid breeding and genetic studies in some of these crops remain less extensive, creating opportunities for the identification of heterotic groups and the development of locally adapted hybrids.

5.5 Pumpkin and Squash

Pumpkin and squash represent another important segment of cucurbit breeding. Hybridization can generate combinations with improved fruit yield, fruit size, uniformity, maturity and quality; a full-diallel evaluation of pumpkin inbred lines across environments reported significant heterosis and non-additive gene action for yield as well as for sweetness, carotenoid content and antioxidant traits, indicating scope for combining productivity gains with nutritional improvement (Hosen et al., 2022). Interspecific breeding within *Cucurbita* spp. has also been explored for transferring useful traits, although compatibility, fertility and the genetic background of parents must be carefully considered. Heterosis breeding can be particularly valuable where hybrids combine vigorous growth with uniform commercial fruit characteristics.

5.6 Muskmelon and Watermelon

Muskmelon and watermelon have a long history of hybrid breeding. Commercial hybrids are valued for high yield, uniform fruit size, flesh quality, sweetness, earliness and marketability. In muskmelon, half-diallel evaluation of genetically diverse inbred lines, including genic male-sterile lines, has demonstrated substantial standard heterosis for fruit yield together with improvements in sweetness, β-carotene content, ascorbic acid, firmness and Fusarium wilt resistance, illustrating how heterosis breeding can be combined with disease-resistance objectives (Kaur et al., 2022). In watermelon, hybrid breeding has similarly been integrated with disease resistance and seedless fruit production systems. Broader reviews of melon breeding note that, relative to major grain and vegetable crops, empirical heterosis and combining-ability studies in cucurbits remain comparatively limited, leaving considerable scope for further work (Kesh & Kaushik, 2021).

6. Mechanisms and Approaches for Hybrid Seed Production

Successful heterosis breeding requires reliable production of genetically pure parental lines and efficient hybrid seed production. In cucurbits, controlled pollination is facilitated by the distinct male and female flowers. Emasculation, where required, is followed by hand pollination and protection of the female flower from unwanted pollen. Gynoecious lines, sex-expression modifiers and other reproductive traits can reduce the cost and labour involved in hybrid seed production (Jat et al., 2015). The choice of parental lines is critical. Breeders generally seek parents that differ sufficiently to generate useful heterosis while possessing complementary desirable traits. Evaluation of parental per se performance, GCA, genetic diversity and combining ability can improve the probability of obtaining superior F_1 hybrids (Griffing, 1956).

7. Advantages of Heterosis Breeding in Cucurbits

- Higher fruit yield and improved yield components.
- Greater earliness and improved synchronization of marketable harvest.
- Improved fruit uniformity, size, shape and market appeal.
- Potential improvement in nutritional and biochemical quality traits.
- Combination of complementary traits from genetically diverse parents.
- Possibility of combining productivity with tolerance to important stresses.
- Efficient exploitation of non-additive genetic variation.

8. Constraints and Challenges

Despite its advantages, heterosis breeding has several constraints. Maintenance of genetically pure parental lines requires careful isolation and selection. Hybrid seed production can be labour-intensive when hand pollination is required. Environmental effects may alter sex expression, flowering behaviour, fruit set and hybrid performance, making multi-location testing essential — a point underscored by the marked differences in heterosis magnitude reported across independent cucumber studies conducted in different germplasm sets and environments (Ene et al., 2019; Cramer & Wehner, 1999). In addition, the cost of hybrid seed can be higher than that of open-pollinated varieties and farmers cannot normally maintain the same level of performance by saving F_1 seed for the next generation. Another major challenge is the identification of stable heterotic patterns. High heterosis in one environment does not necessarily guarantee superior performance in another. Therefore, genotype × environment interaction, parental adaptation and disease pressure must be considered before commercialization.

9. Future Prospects

The future of heterosis breeding in cucurbitaceous vegetables lies in combining conventional breeding with genomic technologies. Development of well-characterized heterotic groups, efficient gynoecious or other reproductive systems, molecular markers for key traits, genomic prediction and precise phenotyping can accelerate hybrid development. Breeding objectives are also expected to expand from yield alone to include nutritional quality, shelf life, climate resilience, water-use efficiency and resistance to emerging pests and diseases, as already illustrated by combined yield-and-quality heterosis studies in pumpkin, muskmelon and bottle gourd (Hosen et al., 2022; Kaur et al., 2022; Bhatt et al., 2023). Climate change makes these objectives particularly important. Hybrids that maintain flowering, fruit set and quality under heat, drought or irregular rainfall could provide greater stability to vegetable production. Integration of farmer preferences and market requirements with genetic improvement will be essential to ensure that new hybrids are not only biologically superior but also commercially useful.

10. Conclusion

Heterosis breeding is a powerful approach for the genetic improvement of cucurbitaceous vegetable crops. The biological features of cucurbits, including diverse sex-expression systems and manageable pollination, make these crops well suited to hybrid development. Considerable heterosis has been documented for yield, earliness, fruit attributes and quality in cucumber, bitter gourd, bottle gourd, ridge gourd, sponge gourd, pumpkin, squash, muskmelon and watermelon.

Combining ability analysis, grounded in the classical frameworks of Griffing (1956) and Hayman (1954), provides an important tool for identifying superior parents and crosses, while molecular and genomic technologies offer new opportunities for predicting and understanding hybrid performance. Future breeding programmes should integrate heterosis with resistance breeding, nutritional quality, stress resilience and modern genomic tools to develop productive, stable and market-oriented cucurbit hybrids.

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Superweeds: A silent Threat to India's Food Security

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Abstract

Superweeds are weeds that survive herbicides that once controlled them effectively. They develop naturally through repeated use of the same herbicide, where a few tolerant weeds survive, produce seeds, and gradually dominate the field. Factors such as climate change, monocropping, and continuous herbicide exposure accelerate this process. As a result, herbicides lose their effectiveness, making weed control more difficult, expensive, and risky for crop production. In India, where agriculture supports millions of livelihoods and ensures national food security, herbicide resistance has become a serious concern. Intensive cropping systems like rice–wheat, along with heavy reliance on chemical weed control, have contributed to the spread of resistant weeds. A notable example is Phalaris minor, which developed resistance to isoproturon. Weeds already cause significant yield losses by competing for nutrients, water, and light, leading to large economic losses for farmers and the agricultural economy. To address this challenge, Integrated Weed Management (IWM) offers a sustainable solution. Preventive measures, herbicide rotation, correct application practices, crop diversification, and non-chemical methods such as mechanical weeding and mulching can reduce resistance development. Long-term management of the weed seed bank and regular field monitoring are essential. Adopting IWM can help control superweeds effectively and protect India's food security.

Keywords

Herbicide resistance, Selection pressure , Monocropping , Integrated Weed Management

Introduction

Weeds are one of the major constraints to crop production because they compete with crops for water, nutrients, light and space. Farmers are increasingly turning to herbicides to control them quickly and effectively, especially in intensive cropping systems. However, the repeated use of the same herbicide or similar herbicides has led to a new problem — herbicide-resistant weeds, commonly called "superweeds." Weeds can survive treatments that were formerly effective and can gradually become dominant in agricultural fields. This problem is especially important in India in intensive systems such as rice-wheat where continuous cropping and heavy reliance on chemical weed control can increase selection pressure. Resistant weeds can increase production costs, decrease yields from crops, and threaten long-term food security.

What are Superweeds?

Superweeds are weeds that do not die even after spraying herbicides that once controlled them easily. In simple words, they are "tough weeds" that have learned how to survive chemicals used to kill them.

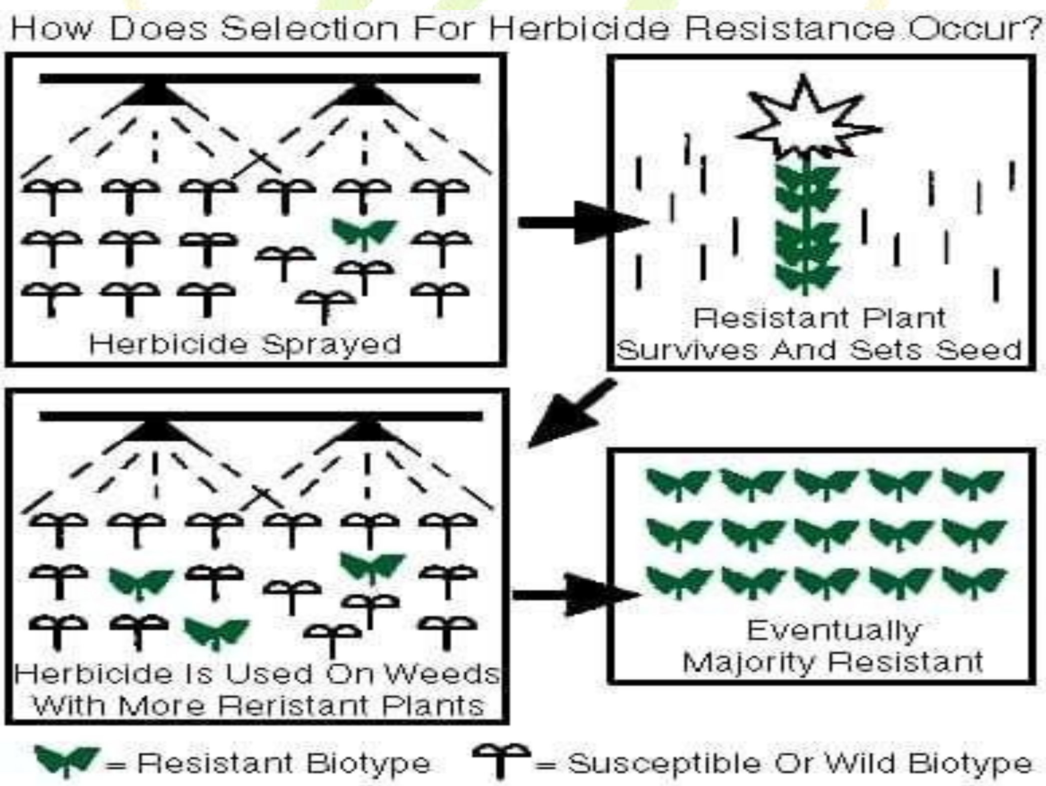
In science, the word superweed is used for weeds that have become resistant to more than one herbicide, even when those herbicides work in different ways. Because of this, these weeds become very difficult and expensive to control.

How do Superweeds develop?

Superweeds are not created in laboratories and they are not artificial. They develop naturally.

When the same herbicide is used again and again for many years, most weeds die. But a few weeds may survive because they naturally have a small tolerance to that chemical. These surviving weeds produce seeds and increase in number.

Over time, these resistant weeds spread in the field, and the herbicide stops working effectively. This process is called natural selection.



What makes superweeds more dangerous?

- Climate change:

  Changing temperatures and weather help weeds adapt faster and survive stress.

- Repeated herbicide exposure:

  Using the same herbicide again and again kills weak weeds but allows naturally tolerant ones to survive.

- Monocropping:

  Growing the same crop year after year creates a uniform system where the same weeds face the same control methods.

- Intense competition / selection pressure:

  These conditions "select" only the toughest weeds—those that can resist control measures.

Result :-

Herbicide effectiveness reduces. Herbicides stop working properly, making weed control more difficult, costly, and risky for food production.

Why herbicide resistance is a serious issue for Indian agriculture?

Weed control is very important for successful farming in India, especially in major crops like rice, wheat, soybean, and cotton. In intensive cropping systems such as the rice–wheat system of Punjab and Haryana, farmers have depended heavily on herbicides for many years. Because of repeated use of the same herbicide, some weeds have slowly learned to survive these chemicals. A well-known example is Phalaris minor, which has developed resistance to the commonly used herbicide isoproturon (Yadav et al., 2017). Over time, these resistant weeds have also become difficult to control with other herbicides, making weed management more complicated.

Across India, weeds already cause large crop losses every year. Due to competition with crops for nutrients, water, and light, weeds reduce yields and increase the cost of cultivation. Studies estimate that annual economic losses due to weeds in India are more than ₹92,000 crore, which puts a heavy burden on farmers and the agricultural economy (Gharde et al., 2018).

Another growing concern is the use of herbicide-tolerant crop varieties. These crops can survive certain herbicides, making weed control easier in the beginning. However, if the same herbicide is used repeatedly in such crops, weeds may develop resistance even faster. This can lead to the emergence of stronger and more difficult-to-control weed populations in the long run (Duke, 2012; Norsworthy et al., 2014).

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Herbicide-Resistant Weeds Reported in India

Sl.	Species	Common Name	First Reported Year	Herbicide Site of Action
1	*Phalaris minor*	Little seed canary grass	1991	PSII inhibitors – Serine 264 binders (C1/C2)
2	*Phalaris minor*	Little seed canary grass	1994	Acetyl-CoA Carboxylase (ACCase) inhibitors (Group A)
3	*Phalaris minor*	Little seed canary grass	2006	**Multiple resistance:** ACCase (A) + ALS (B) + PSII (C)
4	*Phalaris minor*	Little seed canary grass	2013	Acetolactate Synthase (ALS) inhibitors (Group B)
5	*Rumex dentatus*	Toothed dock	2014	Acetolactate Synthase (ALS) inhibitors
6	*Cyperus difformis*	Smallflower umbrella sedge	2017	Acetolactate Synthase (ALS) inhibitors
7	*Echinochloa crus-galli var. crus-galli* (Grassy weed)	Barnyardgrass	2017	Acetolactate Synthase (ALS) inhibitors

A path forward: Integrated Weed Management

The first line of defense is prevention. Using clean seed, preventing the movement of contaminated soil or machinery, and removing weed escapes before seed set can significantly slow resistance development. Farmers should avoid repeated use of the same herbicide and instead rotate herbicides with different modes of action. Applying herbicides at the recommended dose and correct growth stage is equally important, as under-dosing often allows tolerant weeds to survive.

Cropping system diversification plays a key role. Crop rotation, competitive crop varieties, proper spacing, and timely sowing help suppress weed growth naturally. Non-chemical methods such as hand weeding, mechanical intercultivation, mulching, and stale seedbed techniques further reduce weed pressure.

Managing the weed seed bank by preventing seed production ensures long-term control. Regular field monitoring helps detect unusual weed survival early. Ultimately, Integrated Weed Management (IWM) — combining chemical, cultural, and mechanical methods — offers the most sustainable strategy for controlling superweeds and protecting India's food security.

Conclusion

Superweeds are becoming a serious problem, but they can be controlled with proper care. Farmers should not depend on only one herbicide again and again. Using different weed control methods, such as crop rotation, correct herbicide use, and mechanical weeding, can help reduce the risk. Awareness, timely action, and good management are very important. Scientists, extension workers, and farmers must work together to prevent weeds from spreading and becoming stronger. With smart and sustainable practices, we can protect crop yields, reduce losses, and ensure food security. If we act early and wisely, superweeds can be managed and will not threaten Indian agriculture in the future.

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Artificial Intelligence and Employment in India- "Job Creation vs Job Displacement"

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Introduction

India is standing at an unusual crossroads. It has the largest young population in the world, one of the fastest-growing major economies, and, at the same time, one of the fastest-growing appetites for Artificial Intelligence. Walk into an IT services company in Bengaluru, a bank's back office in Mumbai, or a factory floor in Pune today, and AI is already at work somewhere in the process -screening resumes, flagging fraudulent transactions, predicting when a machine will break down, or answering a customer's query before a human ever picks up the phone.

That quiet, steady spread of AI into everyday work has opened up a debate that touches almost every working Indian, directly or indirectly: is AI going to create more jobs than it destroys, or is it going to hollow out the very sectors -IT, BPM, banking, customer support that built India's modern middle class Government reports, industry bodies and international institutions have all weighed in, and the honest answer that emerges from their research is not a clean yes or no. It's "both, depending on what India does next." Some roles will disappear. New ones, many of which don't have a name yet, will take their place. Whether the net result is good for Indian workers depends on how quickly and how seriously the country invests in reskilling, policy, and industry coordination.

This article walks through the evidence for both sides of the argument, lays out the key numbers from credible sources in one place, and closes with some practical suggestions for how India can come out ahead in this transition rather than behind it.

The Case for Job Creation

Start with the optimistic case, because there's real substance to it. As far back as 2019, the Ministry of Electronics and Information Technology projected those digital technologies, AI among them, could help redeploy 40-45 million workers through retraining by 2025, while adding roughly 20 million new jobs in areas like IT-BPM, manufacturing, agriculture, and logistics. A year later, NASSCOM estimated that AI and data could add somewhere between USD 450 and 500 billion to India's GDP by 2025 a figure large enough to reshape entire industries around it.

More recent research backs this up with sharper detail. NITI Aayog's Roadmap for Job Creation in the AI Economy, released in October 2025 in partnership with NASSCOM and Boston Consulting Group, found that if India moves in a coordinated way, its technology and customer experience sector alone could generate up to 4 million new AI-enabled jobs over the next five years. Many of these are roles that simply didn't exist a few years ago AI prompt engineers, AI operations engineers, ethical AI specialists, quantum machine-learning engineers. The World Economic Forum's Future of Jobs research points in a similar direction globally, estimating that while AI could displace around 85 million jobs worldwide by 2025, it could create roughly 97 million new ones in the same window a net gain, even if the composition of the workforce shifts considerably.

Perhaps the most telling data point, though, is how Indian workers themselves feel about it. ADP Research surveyed 38,000 working adults across the world for its People at Work 2025 report and found India to be the second most optimistic country globally about AI's effect on jobs 34% of Indian employees said they expect AI to have a positive impact on their role in the coming year, against just 17% who worry it will replace them outright. That's a strikingly different mood from the anxiety often reported in Western labour markets.

The Case for Job Displacement

The other side of the picture is harder to ignore, and it centres on exactly the sectors that made India's services-led growth story possible. That same NITI Aayog roadmap that projects 4 million new jobs also carries a warning: without decisive action, India's technology sector could see a net loss of over 1.5 million jobs by 2031. The roles most exposed are the routine and repetitive one’s manual software testers, data entry analysts, QA engineers, and Level-1 customer support agents precisely the entry-level jobs that have historically served as the first rung on the career ladder for millions of young graduates.

The scale of what's at stake becomes clearer when you look at how large this sector already is. India's Economic Survey 2025-26 notes that the ICT-BPM industry alone employed 5.4 million people and contributed 7.5% of GDP in 2023. A serious disruption here wouldn't be a niche problem it would ripple through the broader economy. Globally, the IMF has estimated that close to 40% of all employment is exposed to AI in some form; in advanced economies that exposure climbs to around 60% of jobs, roughly split between roles that benefit from AI and roles that see reduced demand because of it. Emerging economies like India show somewhat lower exposure, near 40%, which suggests the disruption may be real but not quite as severe as in wealthier, more automated economies at least for now. Some independent industry analyses have painted a more urgent picture still, warning that a large share of India's white-collar roles in IT, finance and customer service face meaningful AI-driven disruption within the next five years, especially in the most process-heavy, routinised jobs.

Sector-wise Impact

The disruption isn't spread evenly. In IT and BPM, the sector most exposed overall routine work like manual testing, data entry, and first-line support is under the most pressure, even as new AI-first roles open up in parallel. Banking and financial services are seeing similar patterns: AI-driven fraud detection, robo-advisory tools, and automated loan processing are cutting into repetitive back-office and entry-level analyst work, while creating fresh demand for AI risk modelling and compliance specialists. Manufacturing looks somewhat different AI is mostly being used for predictive maintenance and quality control, which tends to make existing skilled workers more productive rather than replace them outright, though repetitive assembly-line tasks remain exposed. Agriculture and logistics are generally seen as net job-creating areas, with AI opening up new technical and support roles around precision farming and supply-chain optimisation. Healthcare, for its part, is largely using AI to support professionals in diagnostics and administrative work rather than replace them, given how much the sector still depends on human judgement and trust.

Data at a Glance

The table below brings together the key figures cited above from government, industry, and international sources. It's worth noting that these studies use different methodologies, time horizons, and definitions of "exposure" or "displacement," so the numbers are best read as indicative ranges rather than figures that can be added or compared directly.

Indicator	Figure / Projection	Source
New jobs from digital/AI redeployment in India (by 2025)	~20 million new jobs; 40-45 million workers redeployed via reskilling	Ministry of Electronics & IT (MeitY), 2019
AI and data's projected contribution to India's GDP by 2025	USD 450-500 billion	NASSCOM, 2020
Potential new AI-enabled jobs in India's tech/CX sector (next 5 years, with coordinated action)	Up to 4 million	NITI Aayog Roadmap for Job Creation in the AI Economy (with NASSCOM & BCG), Oct 2025
Potential net job loss in India's tech sector by 2031 (without timely action)	Over 1.5 million	NITI Aayog Roadmap, Oct 2025
ICT-BPM sector employment and GDP contribution (2023)	5.4 million jobs; 7.5% of GDP	Economic Survey 2025-26, Government of India

Global jobs displaced vs. new roles created (by 2025)	85 million displaced; 97 million new roles created	World Economic Forum, Future of Jobs Report
Global employment exposed to AI	~40% overall; ~60% in advanced economies; ~40% in emerging markets incl. India; ~26% in low-income countries	International Monetary Fund (IMF)
Indian employees optimistic AI will help their jobs (next year)	34% (2nd most optimistic country globally)	ADP Research, People at Work 2025 (38,000 workers surveyed)
Indian employees who fear AI will replace their job	17%	ADP Research, People at Work 2025
India's technology and customer experience (CX) sector size	USD 245 billion	NITI Aayog Roadmap, Oct 2025
Existing technology and CX talent pool in India	Over 9 million professionals	NITI Aayog Roadmap, Oct 2025

Suggestions

None of this needs to end badly for Indian workers, but it won't sort itself out on its own either. A few things seem worth prioritising:

1. Move fast on a coordinated national reskilling push. NITI Aayog's proposed National AI Talent Mission needs to actually happen, and at scale building AI literacy from school onward, not just at the postgraduate level.
2. Focus reskilling resources on the workers most exposed right now those in routine testing, data entry, and L1 support roles rather than spreading efforts too thin across the whole workforce.
3. Deepen the kind of industry-government-academia coordination NITI Aayog modelled with NASSCOM and BCG and extend it to other exposed sectors like banking and manufacturing.
4. Don't forget MSMEs and informal workers. Large companies can absorb the cost of this transition; smaller businesses and informal workers, who make up most of India's workforce, need direct support and affordable access to AI tools.
5. Invest in better, more frequent labour-market data on AI's employment effects, so policy can respond in real time rather than after the fact.
6. Encourage employers to treat AI as a tool for augmenting their workforce and redeploying staff internally, rather than defaulting to headcount cuts.
7. Build stronger safety nets unemployment support, portable benefits, transition assistance for workers who are displaced despite everyone's best efforts.

Conclusion

Put together, the evidence from India's own government bodies, from international institutions like the IMF and WEF, and from industry research by NASSCOM, ADP and BCG tells a fairly consistent story: AI's effect on Indian employment isn't a simple case of jobs won or jobs lost, it's a transition, and a fairly significant one. The technology and services sectors that carried India's growth story for the last three decades face real risk of disruption in their more routine, repetitive roles, particularly as the 2031 horizon approaches. But there's a genuine upside too several million new AI-related jobs could open up if the country moves with enough urgency and coordination.

As NITI Aayog puts it, the difference between a future marked by large-scale job loss and one where India becomes a genuine global hub for AI talent comes down to the choices made now in how seriously reskilling is funded, how well industry and government coordinate, and how much support is extended to the workers most at risk. India has the scale, the young population, and the existing technology talent base to tip this in its favour. What it needs now is speed.

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The GOBARdhan National Circular Bioenergy Scheme (2026): A Policy Perspective on Agricultural Waste, Rural Income, and Energy Security

An Explanation of Policy

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Abstract

In August 2026, the Government of India approved a significantly redesigned version of the GOBARdhan scheme [1]. It has been repositioned and renamed as National Circular Bioenergy Scheme with an outlay of Rs. 23,731 crore for the period FY 2026-27 to FY 2035-36 [1]. Launched in 2018 as a rural sanitation scheme under the Swachh Bharat Mission (Grameen) [2], the scheme has transformed into an integrated national policy for converting agricultural residue, cattle dung and other organic waste into compressed biogas (CBG) and organic manure [3]. The article gives a brief overview of the scheme's objectives, institutional architecture and financial and pricing mechanisms and situates it in the larger framework of India's agricultural residue management, rural income generation and clean energy transition. The article also talks about the early implementation gaps between plant registration and commissioning, offering a balanced view of the scheme's prospects for the agricultural sector.

Keywords: GOBARdhan, compressed biogas, agricultural waste, circular bioeconomy, rural livelihoods, organic manure

Introduction

Agricultural residue and livestock waste have presented a dual challenge to Indian farming systems for decades: as an environmental hazard, usually managed through open burning or unregulated dumping, and as an underexploited economic resource. To fill this gap, GOBARdhan initiative was launched [2]. GOBARdhan is short form of Galvanizing Organic Bio-Agro Resources Dhan [1]. The initiative aims at converting bio-degradable waste into bio-gas and bio-slurry at the village level [2]. The Union Cabinet on 6 August 2026 approved an expanded version of the scheme, renaming it as the National Circular Bioenergy Scheme, to boost the production of compressed biogas by almost ten times over the next decade [1][4].

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From Village Sanitation to National Energy Policy

GOBARdhan was launched in 2018 under the solid and liquid waste management under the Swachh Bharat Mission (Grameen) and the Department of Drinking Water and Sanitation under the Ministry of Jal Shakti is the nodal agency [2]. Its original mandate was rural cleanliness, disease control and modest household level energy generation through individual, cluster and community biogas plants. In the subsequent years, other complementary schemes were launched by various ministries to support specific segments of the compressed biogas value chain, including SATAT (Sustainable Alternative Toward Affordable Transportation), the Market Development Assistance Scheme for organic manure, the Biomass Aggregation Machinery Scheme and the Development of Pipeline Infrastructure Scheme [3][5]. The 2026 restructuring brings these scattered efforts together under one roof [3]. Until now, responsibilities were split across the Ministry of Jal Shakti, the Department of Fertilizers, the Ministry of Petroleum and Natural Gas [1], and the Ministry of New and Renewable Energy — a setup that made coordination difficult and often slowed projects down. Under the new structure, all of this now falls under a single nodal ministry, the Ministry of Petroleum and Natural Gas, so that execution isn't held up by the same bottlenecks as before.

Objectives and Key Components

At the heart of the restructured scheme is an integrated policy framework covering the entire compressed biogas value chain [6]. The goal is ambitious: nearly a tenfold increase in India's domestic CBG production over the scheme period [1][3], alongside stronger rural incomes, better organic waste management, and less reliance on imported natural gas.

To get there, the scheme rests on six main pillars. There's an assured offtake framework, which requires City Gas Distribution entities to procure CBG in line with a rising blending obligation [4]. Producers also get price certainty — an administered rate of Rs. 2,110 per MMBTU, locked in for at least ten years — plus capital support of up to Rs. 2 crore per tonne-per-day of installed capacity for new plants [4][6]. Rounding out the package are pipeline connectivity support, easier access to credit for developers, and ongoing investment in process and technology upgrades.

On the demand side, the blending obligation for CNG (transport) and PNG (domestic) starts at 3% in FY 2026-27, climbs to 4% in FY 2027-28, and settles at 5% from FY 2028-29 onward [4] — giving producers a clear, predictable demand signal to plan around.

Relevance to Agriculture and Rural Livelihoods

For the agricultural sector, the scheme's significance extends well beyond energy policy. By creating a structured market for crop residue, press mud, and cattle dung, GOBARdhan offers farmers, feedstock aggregators, cooperatives, and rural entrepreneurs an additional income stream from material that is otherwise burned or discarded. The bio-slurry and organic manure generated as a co-product of the digestion process is supported through a separate Market Development Assistance subsidy of Rs. 1,500 per tonne, of which more than Rs. 111 crore had already been disbursed as of February 2026 [7], offering a route toward reduced dependence on chemical fertilisers and improved soil health. The scheme is also linked to applied research, including a two-year Indian Council of Agricultural Research project supporting field demonstrations, alongside an ongoing NITI Aayog evaluation of the scheme's overall impact [7]. Collectively, these elements position GOBARdhan as an instrument connecting agricultural waste management with farm-level income diversification and environmental sustainability.

Implementation Gaps and Challenges

Despite this expanded design, early implementation data indicate a persistent gap between registration and commissioning of biogas plants. As of August 2026, only around 217 of 1,908 registered CBG projects were operational, a commissioning rate of roughly 11 per cent, echoing the shortfall seen under the earlier SATAT initiative, which had targeted 5,000 plants by 2024 but fell well short. Commonly cited reasons include inconsistent feedstock supply due to variability in moisture content, seasonality and aggregation logistics, as well as previous failures in coordination across ministries which the 2026 restructuring is specifically aimed at addressing. The real test of the scheme's success over the next few years will be whether the new pricing, offtake guaranties and capital support are sufficient to convert registered capacity into operating plants.

Conclusion

GOBARdhan 2026 is a transition from a rural sanitation program to a consolidated national energy and circular economy policy with substantial financial outlay and an integrated institutional framework [1][3]. This is a policy effort to formalize the economic value of crop residue and livestock waste, primarily for the agricultural sector, and to integrate waste management, farmer income and organic soil amendments into a single framework. The Indian Biogas Association estimates that, if the program is scaled successfully, it could reduce the country's natural gas import bill by nearly five billion US dollars [8]. But these gains will be realized only if the scheme's improved pricing and financing architecture is translated into a much higher rate of plant commissioning than has been achieved so far.

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Overcoming Hidden Hunger in Horticultural Soils: Optimizing Secondary and Micronutrient Management for Crop Quality and Sustainability

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ABSTRACT

Hidden hunger in horticultural soils, resulting from deficiencies of secondary nutrients (calcium, magnesium and sulphur) and micronutrients (iron, zinc, boron, manganese, copper and molybdenum) has become a significant challenge to sustainable horticultural production. Although required in small quantities, these nutrients are essential for plant growth, enzyme activation, chlorophyll synthesis, flowering, fruit development and stress tolerance. Continuous cropping, excessive dependence on NPK fertilizers, low organic matter and soil degradation have accelerated nutrient depletion, leading to reduced yield, poor crop quality and lower nutritional value of horticultural produce. Optimizing secondary and micronutrient management through integrated nutrient management practices is crucial for improving soil fertility, crop productivity and produce quality. Soil and plant tissue testing, balanced fertilization, organic amendments, biofertilizers, foliar application and fertigation enhance nutrient availability and use efficiency while reducing environmental losses. Emerging technologies such as precision nutrient management, nano-fertilizers and digital soil mapping further improve the timely and site-specific supply of nutrients. Adequate nutrition with secondary and micronutrients enhances the quality of fruits and vegetables by increasing vitamin and mineral content, improving colour, flavour, shelf life and marketability and also strengthening crop resilience to biotic and abiotic stresses. A holistic nutrient management strategy integrating conventional and advanced approaches is essential to overcome hidden hunger, maintain long-term soil health and ensure sustainable horticultural production. Such strategies will play a vital role in achieving food and nutritional security while promoting environmentally sustainable agriculture.

Keywords: Hidden hunger, Secondary nutrients, Soil fertility, Precision agriculture, Sustainable horticulture.

INTRODUCTION

Horticulture plays a crucial role in food and nutritional security because fruits and vegetables supply vitamins, minerals, antioxidants, dietary fibre and a range of bioactive compounds. However, the nutritional quality of horticultural produce is closely associated with the availability and balance of nutrients in the soil. Soil fertility is not simply the ability of soil to support plant growth; it involves the capacity of soil to provide essential nutrients along with suitable chemical, physical and biological conditions for plant development.

The concept of **hidden hunger** traditionally refers to deficiencies of essential vitamins and minerals in the human diet, but its roots may extend into the soil–plant system. When soils contain inadequate amounts of available micronutrients, crops may exhibit reduced growth and may accumulate insufficient concentrations of essential minerals in their edible portions. FAO emphasizes the close relationship between soil health, crop quality and nutritional value, highlighting the importance of balanced soil nutrition in addressing micronutrient deficiencies.

Horticultural crops are generally high-value and nutrient-responsive crops and their quality is determined not only by yield but also by nutritional composition, appearance, taste, texture, storage ability and bioactive compounds. Therefore, management of secondary and micronutrients should receive greater attention alongside conventional NPK fertilization.

Secondary and Micronutrients: An Often-Overlooked Component of Plant Nutrition

The essential nutrients required by plants include primary nutrients such as nitrogen, phosphorus and potassium; secondary nutrients such as calcium, magnesium and sulphur; and micronutrients required in smaller quantities. Micronutrients include iron, zinc, manganese, copper, boron, molybdenum and chlorine and nickel. Despite their relatively small quantitative requirements, micronutrients have specific roles in enzyme activity, photosynthesis, metabolism and other essential plant processes. Calcium contributes to cell wall development, membrane stability and cell signalling. Magnesium is the central element of the chlorophyll molecule and is involved in photosynthesis and enzyme activation. Sulphur is essential for protein synthesis and contributes to the formation of important sulphur-containing compounds.

Among micronutrients, iron is essential for chlorophyll formation and electron transport, while zinc contributes to enzyme activity and plant growth regulation. Boron plays important roles in cell wall formation, reproductive development and pollen viability. Manganese is involved in photosynthesis and enzyme activation, while copper participates in several enzymatic processes. Molybdenum is particularly important in nitrogen metabolism. Thus, the deficiency of even a single nutrient can interfere with plant physiological processes and ultimately affect yield and quality.

Causes of Hidden Hunger in Horticultural Soils

The increasing occurrence of secondary and micronutrient deficiencies is closely associated with intensive cropping and imbalanced nutrient management. Continuous removal of nutrients through repeated harvests can gradually deplete soil nutrient reserves. FAO reports that intensive cropping systems can extract substantial quantities of nutrients from soils and that deficiencies may emerge unless adequate nutrient restoration measures are implemented.

The exclusive or excessive emphasis on NPK fertilizers is another important factor. Although NPK fertilizers are essential for achieving high yields, they do not necessarily replenish all nutrients removed by crops. Long-term nutrient imbalance can therefore lead to depletion of secondary and micronutrients.

Low soil organic matter can further reduce nutrient availability and biological activity. Soil pH, texture, moisture, organic matter, redox conditions and interactions among nutrients influence the availability of micronutrients to plants. The availability of micronutrients depends on soil chemical, physical and biological characteristics as well as plant factors. Nutrient antagonism is also important. For example, excessive phosphorus application can induce zinc or iron deficiency under certain soil conditions. Similarly, interactions between calcium, magnesium and other nutrients may affect the availability of micronutrients.

Importance of Secondary and Micronutrients in Horticultural Crop Quality

Secondary and micronutrients influence horticultural crops beyond simple biomass production. Adequate nutrient availability can enhance photosynthesis, root development, flowering, fruit set, cell division and carbohydrate accumulation thereby improving yield and marketable quality. Micronutrients also contribute directly to quality characteristics and improve fruit size, colour, flavour, nutritional value and bioactive compounds while potentially reducing postharvest losses and extending shelf life. Thus, secondary and micronutrient management provides a link between soil fertility, crop productivity, nutritional quality and human health.

Strategies for Optimizing Secondary and Micronutrient Management

1 Soil and Plant Testing: should form the basis of nutrient management. Determination of available nutrient concentrations helps identify deficiencies and prevents unnecessary fertilizer application. Plant tissue analysis can complement soil testing by indicating the actual nutrient status of the crop.

2 Balanced Fertilization: involves supplying nutrients according to crop demand and soil nutrient status rather than concentrating only on NPK. Secondary nutrients such as Ca, Mg and S should be incorporated wherever deficiencies occur along with required micronutrients such as Zn, Fe, B, Mn, Cu and Mo. The objective of balanced fertilization is to maintain nutrient balance rather than simply increasing fertilizer rates. Excessive application of one nutrient may reduce the availability or uptake of another, making balanced fertilization essential for efficient nutrient use.

3 Integration of Organic and Inorganic Sources: Farmyard manure, compost, vermicompost, green manure and crop residues can improve soil organic matter, microbial activity, nutrient cycling, soil structure and water-holding capacity. Combining organic nutrient sources with mineral fertilizers provides a more comprehensive nutrient supply and can improve long-term soil fertility.

4 Biofertilizers and Beneficial Microorganisms: Biofertilizers are defined as the preparations containing live microbes that help in enhancing soil fertility by fixing atmospheric nitrogen, solubilizing phosphorus and decomposing organic wastes and help in plant growth through production of growth promoting hormones. The beneficial microorganisms can improve nutrient availability and facilitate nutrient cycling. The integration of microbial inoculants with organic and mineral nutrient sources can contribute to improved nutrient use efficiency and soil biological health.

5 Soil Application and Foliar Nutrition: Micronutrients may be supplied through soil application or foliar sprays depending on the crop, nutrient and severity of deficiency. Soil application provides nutrients to the root zone whereas foliar nutrition can provide a rapid correction of certain deficiencies, particularly when soil conditions restrict nutrient availability. For horticultural crops, foliar application can be useful during critical stages such as flowering, fruit development and rapid vegetative growth. However, application rates and concentrations should be based on crop requirements to avoid toxicity.

6 Fertigation: allows nutrients to be delivered through irrigation water, particularly through drip systems. It can improve the synchronization between nutrient supply and crop demand, increase nutrient-use efficiency and reduce losses. This approach is particularly suitable for intensive horticultural production where precise management of water and nutrients is important.

7 Precision Nutrient Management: provides opportunities for site-specific management of nutrient deficiencies. Soil nutrient mapping, GPS, GIS, remote sensing, variable-rate application and decision-support tools can help identify nutrient-deficient areas and optimize fertilizer use. These approaches are important because nutrient availability varies spatially within fields. Site-specific application can therefore reduce unnecessary fertilizer use while improving nutrient recovery by crops.

Sustainability and Environmental Considerations

Efficient secondary and micronutrient management is not simply a strategy for increasing crop yield. It is also important for reducing nutrient losses and improving resource-use efficiency. Excessive or inappropriate fertilizer application can result in nutrient accumulation, leaching, runoff and environmental contamination.

Sustainable nutrient management therefore requires the **right source, right rate, right time and right method** of nutrient application. The judicious fertilizer management, nutrient measurement and mapping, crop diversification, long-term soil management and appropriate micronutrient use are key approaches to correcting nutrient imbalances.

Conclusion

Hidden hunger in horticultural soils represents an important challenge for sustainable crop production because deficiencies of secondary and micronutrients can simultaneously affect soil fertility, plant growth, crop yield and nutritional quality. Continuous cropping, imbalanced fertilization, declining soil organic matter and adverse soil conditions can increase the risk of nutrient deficiencies.

A holistic approach based on soil and plant testing, balanced fertilization, integrated use of organic and inorganic nutrient sources, biofertilizers, foliar nutrition, fertigation and precision nutrient management can help overcome these limitations. Appropriate management of secondary and micronutrients can improve not only productivity but also nutritional quality, marketability and postharvest performance of horticultural crops. Therefore, the future of sustainable horticulture lies in shifting from **"more fertilizer" to "better-balanced nutrition."** Optimizing nutrient supply according to soil status, crop demand and environmental conditions can help produce healthier crops, restore soil fertility and contribute to improved nutritional security which offers a promising pathway towards resilient, resource-efficient and nutritionally sensitive horticultural production.

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Integrated Nutrient Management : A Key to Sustainable Soil Health and Vegetable Production

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1. Introduction

Vegetables are a key part of a healthy diet because they provide important vitamins, minerals, dietary fibre and antioxidants that keeps the body healthy. Vegetable cultivation not only provides nutritious food but also helps farmers earn more money, creates job opportunities and supports the growth of the horticulture industry. India is the second largest country in the world when it comes to growing vegetables. Every year, it produces over 221 million tonnes of vegetables from about 11.88 million hectares of land (Ministry of Agriculture and Farmers Welfare, 2025). This shows how important vegetable farming has become in providing enough food and good nutrition for the growing population.

Vegetable crops deplete soil nutrients rapidly due to their fast growth, limited root depth, and high biomass output. To boost yield, farmers frequently apply chemical fertilizers. While such fertilizers have greatly enhanced productivity, their prolonged and unbalanced use—especially without sufficient organic inputs—has led to nutrient imbalances, reduced soil organic matter, degraded soil structure, lower microbial activity and environmental contamination. These issues pose serious risks to sustained soil fertility and the long-term viability of vegetable farming (Chaudhari et al., 2023; Verma and Yadav., 2024).

Integrated Nutrient Management (INM) has emerged as an efficient and effective solution to the problems as it focuses on the judicious use of inorganic fertilizers along with organic manures. It includes the use of crop residues, green manures and biofertilizers to supply nutrients to the soil and crops in a balanced manner. The use of these nutrients increases the use efficiency of inorganic fertilizers and promotes sustainable agriculture by improving the physical, chemical and biological properties of the soil. Apart from this, INM practices have also improved the yield, quality, nutrient content and profitability of vegetable crops while conserving the natural resources (Chaudhari et al.,2023; Verma and Yadav.,2024).

In the context of climate change, soil degradation and the need for sustainable and healthy food, INM has gained significant importance for the effective production of vegetables. This article focuses on the concept, components, benefits and future scope of integrated nutrient management (Himanshu et al., 2026; Muradi et al., 2026).

2. What is Integrated Nutrient Management?

Integrated Nutrient Management focuses on the judicious use of chemical fertilizers in combination with organic and bio-fertilizers to maintain soil health and ensure good crop production. The main objective of INM is not only to increase crop yield but also to maintain soil productivity for future generations. In contrast to conventional fertilizer practices that mainly depend on inorganic fertilizers, INM integrates organic manures, biofertilizers and chemical fertilizers to meet crop nutrient requirements while enhancing soil quality (Chaudhari et al., 2023; Verma and Yadav., 2024).

3. Components of Integrated Nutrient Management

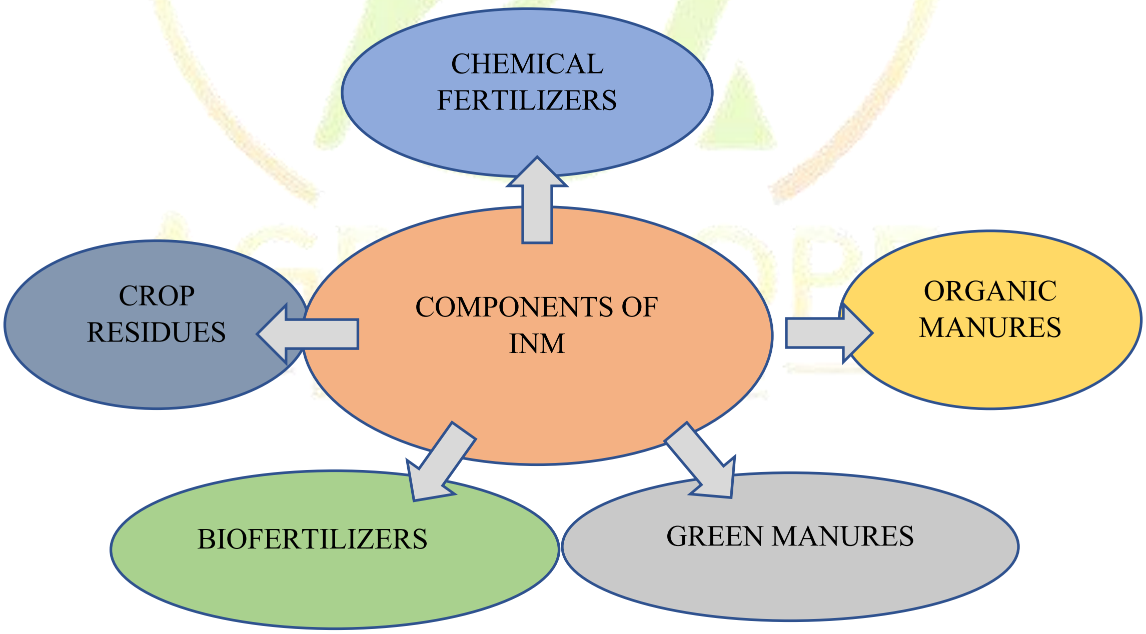

Fig. 1- Components of Integrated Nutrient Management.

3.1. Chemical fertilizers

Chemical fertilizers play a key role in integrated nutrient management (INM) by providing essential nutrients—nitrogen (N), phosphorus (P) and potassium (K)—in forms that plants can easily absorb. The application of chemical fertilizers in INM is done in judicious manner as per the soil test reports and this avoid nutrient loss and pollution. In addition, the use of chemical fertilizers as a component of INM is combined with organic manures and fertilizers for enhanced nutrient utilization (Chaudhari et al., 2023).

3.2. Organic manures

The organic manures like farmyard manure, compost, vermicompost, poultry manure, crop residues etc. helps in improving the organic carbon content in the soil. They also enhances the soil structure, increases water holding capacity and accelerates the activity of micro-organisms in the soil. In addition, organic manures provides a steady supply of nutrients that improve the fertility of soil (Chaudhari et al., 2023; Verma and Yadav., 2024).

3.3. Green manures

Green manures are cultivated specifically for incorporation into the soil at the flowering stage and serve to improve the fertility of the soil. They improve the soil structure, add organic matter to the soil, fix atmospheric nitrogen, improve the activity of other microorganisms and hence increase the availability of nutrients in the soil and reduce the dependency on chemical fertilizers (Chaudhari et al., 2023).

3.4. Biofertilizers

Biofertilizers are fertilizers that contain nitrogen fixing microorganisms which promote nutrients absorption, enhance growth of plants, improve soil structure and increase biological activity in the soil thus reducing the need for chemical fertilizers. Common biofertilizers used in vegetable production include:

- Azotobacter – fixes atmospheric nitrogen.
- Azospirillum – promotes root growth and nitrogen fixation.
- Phosphate Solubilizing Bacteria (PSB) – converts insoluble phosphorus into available forms.
- Potassium Solubilizing Bacteria (KSB) – enhances potassium availability.

- Arbuscular Mycorrhizal Fungi (AMF) – improve phosphorus uptake, water absorption and stress tolerance (Kumar et al., 2022).

3.5. Crop residues

The plant materials left in the field after harvest such as stems, leaves, roots etc are called as crop residues. The incorporation of these residues into the soil promotes nutrient cycling, enhances soil organic matter, stimulates microbial activity and ensure sustainable vegetable production further (Ali et al., 2024; Kamboj et al., 2024).

4. Role of Integrated Nutrient Management in Improving Soil Health

Integrated Nutrient Management plays a crucial role in improving soil health. It enhances physical, chemical and biological properties of soil which in turn increases nutrient availability, boosts soil fertility and supports sustainable vegetable production (Ali et al., 2024; Kamboj et al., 2024).

Physical Properties

- Improves soil structure and aggregation.
- Increases porosity and water-holding capacity.
- Enhances soil aeration and infiltration.
- Reduces soil compaction and erosion.
- Promotes healthy root growth (Ali et al., 2024; Kamboj et al., 2024).

Chemical Properties

- Increases soil organic carbon content.
- Improves availability of macro and micronutrients.
- Enhances cation exchange capacity (CEC).
- Maintains favourable soil pH.
- Improves nutrient use efficiency and reduces nutrient losses (Kamboj et al., 2024; Sande et al., 2024).

Biological Properties

- Increases beneficial soil microbial populations.
- Enhances microbial biomass and enzyme activity.
- Promotes biological nitrogen fixation and phosphorus solubilization.
- Accelerates decomposition of organic matter.

- Improves nutrient cycling and soil fertility (Kamboj et al., 2024; Verma and Yadav., 2024).

5. Role of Integrated Nutrient Management in Vegetable Production

5.1. Enhanced Growth and Yield

The integrated nutrient management approach ensures the supply of balanced plant nutrients by combining the use of inorganic fertilizer with organic and biological sources, resulting in improved vegetative and reproductive growth, improved root development and photosynthetic performance, thereby increasing vegetable yield. The combined application of organic and inorganic fertilizers sustains productivity during intensive vegetable production ((Kamboj et al., 2024; Verma and Yadav., 2024).

5.2. Improved Quality of Vegetable Produce

In addition to improving crop yield, INM also improves the nutritional and market value of the vegetables. The availability of nutrients in balanced amount improves the size, colour, firmness and shelf life of the produce while increasing the vitamin C content, total soluble solids (TSS), sugars and antioxidants. Hence, the vegetables are of better quality and fetch higher prices in the market than those obtained from plants grown solely with chemical fertilizers (Verma and Yadav., 2024).

5.3. Efficient Nutrient Utilization and Profitability

The combined use of chemical fertilizers with organic manures and biofertilizers increases the nutrient use efficiency because it synchronizes the nutrient supply with plant demand and reduces the loss of nutrients. It lowers the use of chemical fertilizers and thus reduces the cost of cultivation. This ultimately improves the benefit-cost ratio and increases the profitability of the vegetable crops (Kamboj et al., 2024; Chaudhari et al., 2023).

5.4. Sustainable Vegetable Production

The integrated use of organic and biological inputs ensures conservation of natural resources, minimizes environmental degradation and supports long term productivity of vegetable based cropping systems. Thus, INM plays crucial role in sustainable and profitable vegetable production (Ali et al.,2024; Sande et al.,2024).

Crop	*Integrated Nutrient Management Practice (INM)*	*Major effects observed*
Tomato (Solanum lycopersicum L.)	***50% Recommended dose of fertilizer (RDF) +AgroResidue Vermicompost (5 t ha^{-1})***	***Improved plant growth, chlorophyll content, flowering, fruit number and fruit yield.***
Chilli (Capsicum annuum L.)	***75%fertilizers+Poultry manure(5 t ha^{-1}) + Biofertilizers + $MgSO_4$(2%)***	***Increased plant height leaf area, branching, fruit yield, and nutrient uptake.***
Brinjal (Solanum melongena L.)	***100% NPK + 25% N through vermicompost***	***Enhanced fruit size, fruit number and marketable yield.***
Cucumber (Cucumis sativus L.)	***RDF + Vermicompost (5 t ha^{-1}) + Azotobacter (5 kg ha^{-1}) + PSB (5 kg ha^{-1})***	***Increased fruit yield and improved nutrient use efficiency.***
Cauliflower (Brassica oleracea var. botrytis)	***100%RDF + Azospirillum (5 L ha^{-1}) + PSB (5 L ha^{-1}) + KMB (5 L ha^{-1})***	***Improved curd development, quality and marketable yield.***
Cabbage (Brassica oleracea var. capitata)	***FYM (50%) + Azotobacter (50%)***	***Enhanced head development, leaf growth and earliness.***
Onion (Allium cepa L.)	***FYM(20tha^{1})+Vermicompost (5t ha^{-1}) + Poultry manure (2 t ha^{-1}) +100% Recommended NPK***	***Increased bulb size, bulb yield, neck thickness and plant vigour.***

Table 1. Effect of Integrated Nutrient Management on Major Vegetable Crops (Ali et al., 2024)

6. Challenges in Adoption of INM

Though INM has been proved to be beneficial but still its adoption is limited due to following reasons:

- Limited awareness and technical knowledge about INM among farmers.
- Scarcity of bio fertilizers.
- High cost for transportation of bulky organic matter.
- Limited availability of laboratories for soil analysis.
- Slow release of nutrients from organic sources.

- Insufficient extension services and supportive policies for promoting large scale adoption of INM (Ali et al., 2024; Kamboj et al., 2024; Verma and Yadav., 2024).

7. Future Prospects

The future of sustainable vegetable production is closely linked to the widespread adoption of integrated approaches such as integrated nutrient management (INM) combined with precision farm management, digital soil health technologies, nano-fertilizers, fertigation and artificial intelligence (AI)-driven nutrient management advisory systems. The future of nutrient management in vegetables will rely on the extensive use of INM coupled with climate-smart technologies to improve nutrient use efficiency, to increase vegetable yield, quality and to reduce environmental degradation (Ali et al., 2024; Kamboj et al., 2024).

Additionally, government-led programs such as the Soil Health Card Scheme, organic farming, balanced fertilization, and farmer training initiatives will promote the adoption of INM at a larger scale. Continued research and the development of site-specific nutrient management approaches will further strengthen the role of INM for profitable, sustainable and climate-resilient vegetable production (Verma and Yadav., 2024).

8. Conclusion

Integrated Nutrient Management (INM) is a nutrient management practice that focuses on improving crop production through the effective use of inorganic fertilizers combined with organic manures, biofertilizers, green manures and crop residues**.** INM is a sustainable and efficient nutrient management approach that can be used to provide balanced nutrition to crops. In the context of vegetable production, INM has tremendous potential for improving plant growth, yield, enhancing produce quality and promoting resource use efficiency while reducing environmental pollution. Its adoption also helps in promoting environment-friendly agricultural practices that conserve natural resources and prevent nutrient losses.

Considering the current environmental issues such as degradation, pollution and global warming, INM is necessary for sustainable vegetable production. Advancing knowledge on INM together with intensification of soil testing services and utilizing new innovations in combination with INM approaches will enhance its impact on vegetable production. Therefore, integrated nutrient management is a key to achieve high-value, environment friendly vegetable production (Kamboj et al., 2024); Verma and Yadav., 2024).

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Packaging in Vegetable Crops: An Essential Tool for Reducing Post-Harvest Losses and Enhancing Marketability

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Abstract

Vegetables are highly perishable commodities due to their high moisture content and rapid physiological activities after harvest. Inadequate packaging during handling, storage, and transportation results in considerable quantitative and qualitative losses, affecting both farmers and consumers. Packaging is an essential component of post-harvest management that protects vegetables from mechanical damage, moisture loss, microbial contamination, and physiological deterioration. Recent advances in packaging technologies, including modified atmosphere packaging (MAP), active packaging, smart packaging, biodegradable materials, and edible coatings, have significantly improved the shelf life and quality of fresh vegetables. Appropriate packaging also enhances marketability, reduces transportation losses, and facilitates domestic and international trade. Adoption of eco-friendly and innovative packaging materials will play a crucial role in reducing post-harvest losses and promoting sustainable vegetable production.

Keywords: Vegetable packaging, post-harvest management, modified atmosphere packaging, biodegradable packaging, shelf life, vegetables.

Introduction

Vegetables constitute an important component of human nutrition by supplying essential vitamins, minerals, dietary fiber, antioxidants, and phytochemicals. However, fresh vegetables are among the most perishable agricultural commodities because they continue to respire and lose moisture after harvest. According to the Food and Agriculture Organization (FAO, 2023), post-harvest losses of fruits and vegetables in developing countries may range from 20 to 30%, primarily due to improper harvesting, handling, packaging, storage, and transportation. Packaging is a vital post-harvest operation that protects vegetables from physical injury, contamination, and environmental stress while maintaining their quality throughout the supply chain. Modern packaging technologies not only reduce post-harvest losses but also improve consumer acceptance, food safety, and export potential (Kader, 2002).

Importance of Packaging in Vegetable Crops

Packaging performs several important functions during the marketing of vegetables. It protects produce from bruising, compression, and vibration during handling and transportation. Proper packaging minimizes moisture loss, slows respiration, reduces microbial infection, and preserves freshness. It also facilitates grading, labeling, storage, and efficient transportation. Attractive packaging enhances consumer confidence and increases the market value of vegetables (Kader, 2002).

Types of Packaging

Packaging used for vegetables can be broadly classified into primary, secondary, and tertiary packaging.

Primary packaging is in direct contact with vegetables and includes polyethylene bags, plastic films, trays, punnets, and mesh bags. Secondary packaging protects primary packages during storage and transportation and generally consists of corrugated fibreboard boxes, plastic crates, and wooden boxes. Tertiary packaging is designed for bulk transportation and export using pallets, shrink wrapping, and large plastic containers.

Packaging Materials Used in Vegetables

Several packaging materials are commonly used depending on the commodity and market requirements.

Plastic crates are widely preferred because they are reusable, durable, lightweight, and provide proper ventilation. Corrugated fibreboard (CFB) boxes are commonly used for export and long-distance transportation due to their excellent strength and cushioning properties. Plastic films such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) reduce moisture loss and improve shelf life. Mesh bags are mainly used for onion, garlic, and potato because they allow adequate air circulation. Transparent plastic punnets and clamshell containers are extensively used for mushrooms, cherry tomatoes, baby vegetables, and leafy greens.

Recent Advances in Vegetable Packaging

Modern packaging technologies have transformed vegetable marketing and storage.

Modified Atmosphere Packaging (MAP) alters the gaseous composition surrounding vegetables, reducing oxygen concentration and increasing carbon dioxide levels to slow respiration and delay senescence.

Active packaging incorporates oxygen scavengers, moisture absorbers, ethylene absorbers, and antimicrobial compounds that actively maintain product quality.

Smart packaging uses freshness indicators, QR codes, RFID tags, and temperature sensors to monitor storage conditions and product quality throughout the supply chain.

Edible coatings prepared from aloe vera gel, chitosan, starch, alginate, and pectin form biodegradable protective layers on vegetables that reduce moisture loss and microbial spoilage while maintaining freshness.

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Source: Content compiled from FAO (2023), Kader (2002), NHB (2023), and AI-generated illustrations created using OpenAI ChatGPT.

Role of Packaging in Reducing Post-Harvest Losses

Proper packaging significantly reduces post-harvest losses by minimizing mechanical injuries, reducing water loss, maintaining nutritional quality, delaying microbial spoilage, and extending shelf life. Packaging also improves stacking efficiency, facilitates long-distance transportation, and ensures that vegetables reach consumers in better condition.

Sustainable Packaging

Growing environmental concerns have encouraged the development of biodegradable packaging materials derived from starch, cellulose, polylactic acid (PLA), and agricultural residues. Such materials reduce plastic pollution while maintaining adequate protection of vegetables. Eco-friendly packaging is becoming increasingly important for sustainable horticultural production systems (Rhim *et al*., 2021).

Challenges

Despite considerable progress, several challenges limit the adoption of modern vegetable packaging technologies. High packaging costs, lack of awareness among farmers, inadequate cold chain infrastructure, limited recycling facilities, and environmental concerns associated with plastic waste remain major constraints. Capacity building, investment in cold chain systems, and policy support are essential to improve packaging practices.

Future Prospects

The future of vegetable packaging lies in biodegradable polymers, nanotechnology-based packaging, intelligent packaging systems, blockchain-enabled traceability, and Internet of Things (IoT)-based monitoring. Integration of these technologies with efficient cold chain management will reduce post-harvest losses, improve food safety, and strengthen the competitiveness of vegetable supply chains.

Conclusion

Packaging has become an indispensable component of post-harvest management in vegetable crops. Appropriate packaging materials and modern packaging technologies effectively reduce post-harvest losses, extend shelf life, improve marketability, and ensure food safety. Adoption of sustainable and innovative packaging systems will contribute significantly to enhancing farmers' income, minimizing food waste, and strengthening national food and nutritional security.

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Plant bio- stimulants in vegetable crops mechanism application and future prospects

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Abstract

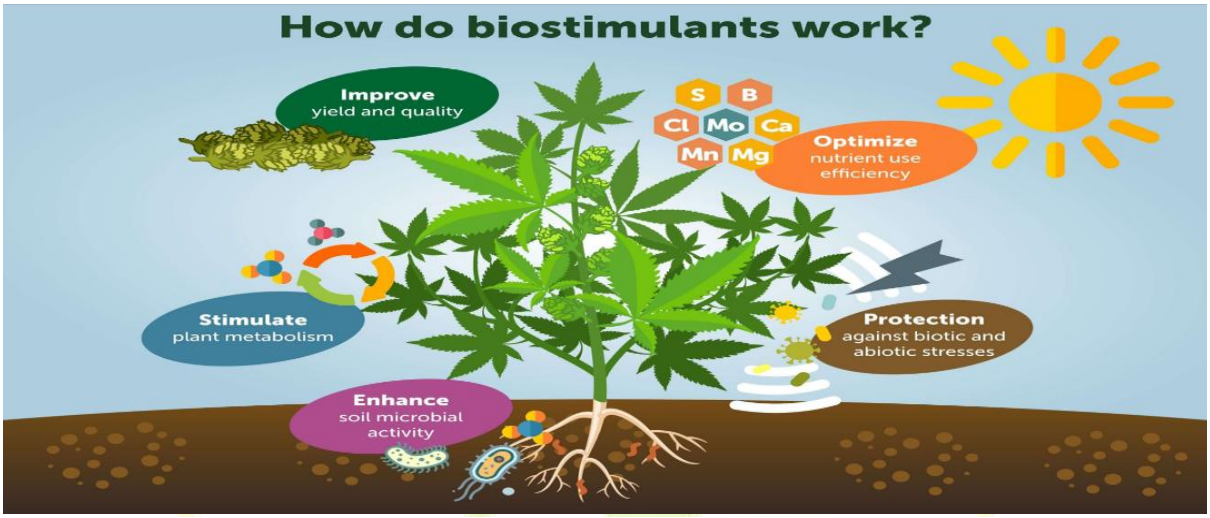
Plant bio-stimulants are natural substances or beneficial microorganisms that enhance plant growth, nutrient uptake, stress tolerance, and crop productivity without acting as conventional fertilizers. Major bio-stimulants include seaweed extracts, humic and fulvic acids, protein hydrolysates, amino acids, beneficial microbes such as PGPR and arbuscular mycorrhizal fungi (AMF), and chitosan-based products. These compounds improve root development, photosynthetic efficiency, nutrient absorption, antioxidant activity, and resistance to abiotic stresses such as drought, salinity, and heat. In vegetable crops, bio-stimulants enhance seed germination, plant vigour, yield, quality, and shelf life while reducing dependence on chemical fertilizers. They can be applied through seed treatment, foliar spray, soil drenching, or fertigation. Despite their promising benefits, challenges such as inconsistent field performance, product standardization, and limited farmer awareness remain. crop-specific formulations, understanding molecular mechanisms, and integrating bio-stimulants into sustainable and climate-resilient vegetable production systems. (Du Jardin *et al.*, 2015)

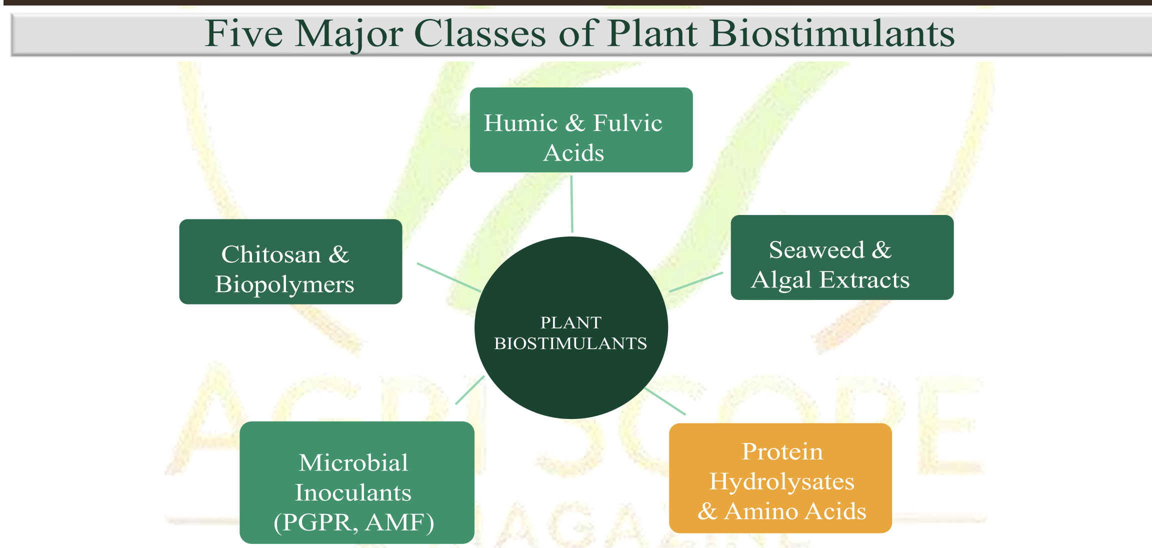
Keywords: Plant bio-stimulants, seaweed extract, humic acid, PGPR, AMF, vegetable crops

INTRODUCTION

Vegetables are an essential component of the human diet, providing vital nutrients, vitamins and minerals. However, intensive cultivation practices, declining soil fertility and climatic challenges often limit vegetable productivity. Nowadays farmers are more inclined to get benefited by the various alternate. systems therefore indiscriminate use of chemicals is more popular. In recent years, bio-stimulants have gained importance as a sustainable tool to boost growth and yield in vegetables while maintaining ecological balance. Biostimulants are the natural formulation extracted from different seaweeds. plants and other materials. According to the European Biostimulants Industry Council (EBIC),

bio-stimulants are substances or microorganisms that stimulate natural processes in plants, improving nutrient uptake efficiency, abiotic stress tolerance and crop quality





Seaweed Extracts

Seaweed and algal extracts are bio-stimulant products obtained from marine algae. They contain various bioactive compounds, minerals, polysaccharides, and plant growth-promoting substances. They can stimulate several physiological processes in plants and are mainly used to improve seed germination, root development, shoot growth, nutrient uptake, stress tolerance, and fruit quality. (Du Jardin *et al*., 2015)

Major effects:

- Improve seed germination and seedling establishment.

- Promote root and shoot development.
- Improve nutrient uptake and utilization.
- Support photosynthetic activity.
- Improve tolerance to environmental stresses.
- Enhance fruit and vegetable quality.

Humic and Fulvic Acids

Humic and fulvic acids are organic substances mainly derived from decomposed organic matter. They are important biostimulant substances that can improve the soil environment as well as plant nutrient acquisition. Their major role is to improve nutrient availability, nutrient uptake, root development and soil structure. Better root-zone conditions can help plants utilize available nutrients and water more efficiently.

Major effects:

- Promote root growth and development.
- Improve nutrient uptake.
- Improve soil structure.
- Enhance the root-zone environment.
- Support plant growth and development.
- Improve nutrient-use efficiency.

Protein Hydrolysates and Amino Acids

Protein hydrolysates are obtained through the breakdown of proteins into smaller peptides and amino acids. They can provide organic nitrogen and stimulate important physiological and biochemical processes in plants Amino acids are involved in several metabolic processes, while protein hydrolysates can stimulate enzyme activity and support plant growth. (Du Jardin *et al*., 2015)

Major effects:

- Provide organic nitrogen.
- Stimulate enzyme activity.
- Support chlorophyll synthesis.
- Promote plant growth and development.
- Improve nutrient-use efficiency.
- Support stress tolerance.
- Improve yield and crop quality.

Microbial Bio-stimulants

Microbial biostimulants contain beneficial microorganisms that interact positively with plants and their root-zone environment. Examples include Azospirillum, Bacillus and Trichoderma. These microorganisms can improve nutrient availability and contribute to plant health and disease resistance.

Major effects:

- Improve nutrient availability.
- Promote root development.
- Enhance rhizosphere activity.
- Support plant growth.
- Improve disease resistance.
- Support tolerance to environmental stresses.
- Improve beneficial soil microbial activity.
- Important groups: PGPR (Plant Growth-Promoting Rhizobacteria) and AMF (Arbuscular Mycorrhizal Fungi).

Chitosan and Other Natural Compounds

Chitosan is a natural biopolymer that can act as a plant biostimulant by stimulating the plant's natural defence responses. It is particularly useful in helping plants respond to environmental stresses such as drought and salinity. Chitosan can therefore contribute to improved plant resilience under unfavourable growing conditions. (Du Jardin *et al*., 2015)

Major effects:

- Stimulates natural plant defence responses.
- Supports drought tolerance.
- Supports salinity tolerance.
- Enhances stress-response mechanisms.
- Supports plant growth and quality.
- Helps plants cope with environmental stresses.

Mechanisms of Action

Biostimulants Act Through Multiple Physiological And Biochemical Pathways:

Enhanced Nutrient Uptake: Stimulate root growth and nutrient absorption.

Improved Photosynthesis: Increase chlorophyll content and enzymatic efficiency.

Stress Tolerance: Activate antioxidant systems to combat drought, heat, and salinity.

Improved Soil Microbiome: Support beneficial microbial communities that enhance soil fertility.

Quality Enhancement: Improve flavor, color, vitamin content, and shelf life of vegetables (Colla *et al*., 2017)

Seaweed Application in different crops

Seaweed Species	Crop	Concentration	Treatment Response
Ascophyllum nodosum	Tomato	0.2–0.5%	Improved germination 20–30%; root length 18–25%; shoot length 15–25%; seedling dry weight 20–35%
Ascophyllum nodosum	Onion	0.2–0.3%	TSS 8–10%; N, P & K uptake 8–15%; bulb weight 10–20%; yield 18–30%
Ascophyllum nodosum	Carrot	0.2–0.4%	Increase in soil microbial activity 20–35% and yield 15–25%

Application in Vegetable Crops

Crop	Bio-stimulant	Observed Effect
Tomato	Humic acid	Increased fruit yield 20–30% and lycopene content 15–25%
Cucumber	Microbial inoculants	Enhanced nutrient uptake 15–25% and disease resistance 20–30%
Onion	Protein hydrolysate	Improved bulb size 15–25% and shelf life 20–30%
Capsicum	Chitosan	Stress tolerance 20–35% and fruit firmness 10–20%
Spinach	Amino acid formulation	Higher chlorophyll content 20–35% and leaf area 15–30%

(Rouphael and Colla., 2020)

Advantages of Using Bio-stimulants

1. Environmentally friendly and biodegradable
2. Reduce dependence on chemical fertilizers and pesticides
3. Enhance soil health and fertility
4. Improve crop yield and quality
5. Compatible with organic farming practices

Challenges and Future Prospects

Bio-stimulants faces certain challenges such as product standardization, variable field performance, and limited awareness among farmers. Future research should focus on:

1. Molecular mechanisms of bio-stimulant action
2. Development of crop-specific formulations
3. Integration with precision agriculture technologies.

4. Regulatory frameworks to ensure quality and efficacy

Conclusion

Bio-stimulants represent a revolutionary approach in modern vegetable production, promoting sustainable and resilient farming systems. their integration into conventional and organic vegetable cultivation can significantly improve productivity, quality, and environmental sustainability. with continued. research and awareness, bio-stimulants can play a pivotal role in achieving the goals of climate-smart and eco-friendly agriculture

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The RNA Revolution: A New Era of Residue-Free Crop Protection in Horticulture

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Chemical pesticides are widely used in horticulture to produce high-quality fruits and vegetables, including flowers, for the global market. A wide range of insecticides and acaricides are used to control lepidopteran larvae, aphids, whiteflies, thrips, mites and fruit flies, while fungicides and bactericides are commonly applied to control *Fusarium*, *Alternaria*, *Phytophthora*, *Botrytis* and powdery mildew on various horticultural crops. However, the frequent and extensive use of these pesticides on vegetable and fruit crops can give rise to problems such as pesticide resistance, pesticide residues on fresh produce, adverse effects on pollinators and beneficial organisms in the agro-ecosystem, environmental contamination, and health problems for farm workers and consumers. Currently, with the strict regulations of Maximum Residue Limits (MRLs) on fresh produce in both domestic and foreign markets, there is a growing need for horticulture to develop accurate, environmentally friendly, and residue-free methods for crop protection. Next-generation RNAi-based biopesticides are likely to meet these requirements and to reduce the use of chemical pesticides for sustainable horticulture.

RNA- Based Biopesticides

Ribonucleic acid (RNA), in particular double-stranded RNA (dsRNA), is the key to next-generation crop protection. In addition to its role in gene expression, dsRNA can also elicit the highly conserved RNA interference (RNAi) pathway, which acts by silencing essential genes that are vital for pest's and pathogen's survival, development, reproduction or pathogenicity. The action of RNA-based biopesticides is based on sequence-specific recognition of target genes based on sequence complementarity rather than non-specific recognition in conventional broad-spectrum pesticides. This allows for highly specific targeting of genes in pests/ pathogens with the possibility of reduced impact on beneficial and non-target organisms.

One Technology, Multiple Targets

The use of dsRNA sequences has been demonstrated to protect horticultural crops from several agricultural issues concerning diseases and pests through RNA interference technology. The five major target categories are provided in Table 1.

Table 1. Gene Target Categories for Precision RNAi-Based Crop Protection Studies

Target category	Representative genes	Examples	Importance
RNAi machinery	DCL1, DCL2, Ago2	*Botrytis, Podosphaera, Plasmopara, Sclerotinia*	Disrupts the pathogen's own RNA-silencing machinery
Essential metabolism	CYP51/ERG11, ATPD, ATPG	*Fusarium, Botrytis, aphids*	Targets essential metabolic processes
Structural/ cytoskeletal genes	TUB2, CHS	*Podosphaera, fungal pathogens*	Disrupts cell structure, growth and development
Virulence-associated genes	CgLAC, pgxB, Tup1	*Colletotrichum, Aspergillus, Fusarium*	Directly interferes with pathogenicity
Insect survival/ development genes	AChE, PBAN, TPS, chitinase, Snf7/mesh	Lepidopterans, aphids, whiteflies, beetles	Cause mortality, developmental defects or reduced reproduction

Cellular Process of RNAi Technology

RNAi-based horticultural protection relies on a highly coordinated process within the pest cell which involves five steps: (i) The application of the dsRNA and its subsequent uptake by the pest, (ii) an enzyme called dicer, which cuts the long dsRNA into small pieces called small interfering RNAs (siRNAs), (iii) loading the small pieces of dsRNA (siRNAs) into the RNA-induced silencing complex (RISC), (iv) the RISC using one strand of the siRNA to guide the targeting of the pest's mRNA, and (v) the RISC complex cleaving the mRNA, thereby preventing the pest from producing a protein that is essential for their survival, reproduction, or virulence (Figure 1).

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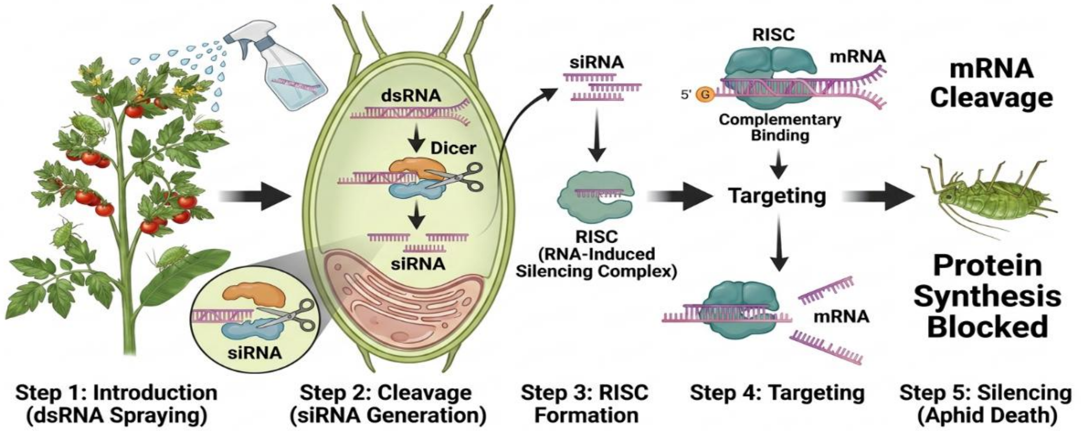

Figure 1: Foliar spray of dsRNA inhibits protein synthesis in aphids

Smart Delivery for Better Protection: Reaching the Right Target

The success of RNA-based bio-pesticides depends on the survival of the RNA, its delivery to the target, and its activity in the target. The activity of dsRNA can be greatly diminished by UV light, rain, nucleases, gut enzymes of insects, and the inability to enter cells. Smart delivery systems are thus being developed to facilitate stability, transport, and precision of RNA.

- **Host-induced gene silencing (HIGS):** Plants as 'RNA Factories' produce dsRNA against invading pests/pathogens. HIGS transgenic plants are commonly produced by Agrobacterium-mediated transformation. For instance, HIGS has been developed to control root-knot nematode and has decreased nematode reproduction by 73.75% in tuberose.
- **Virus-induced gene silencing (VIGS)** is a method that makes use of a modified viral genome as a VIGS vector to produce efficient siRNA for the target gene. Tobacco Rattle virus (TRV) based VIGS has been considered the most popular target system due to its systemic movement and high host range. For instance, TRV-based VIGS silences the *LeCTR1* gene and improves the plant's tolerance to tomato leaf curl virus.
- **Spray-induced gene silencing (SIGS):** It has two pathways: direct uptake when the pest or pathogen is directly absorbed by the plant surface, triggering the RNAi mechanism; and indirect uptake when the plant absorbs the dsRNA and then triggers the RNAi mechanism when fed or infected by a pest or pathogen. Successful applications include control of important diseases like gray mold, white mold, late blight, Asian soybean rust and tobacco mosaic virus, and insect pests like the diamondback moth, whitefly, Asian citrus psyllid, soybean aphid and other leaf-chewing insects. For example, an application of this dsRNA

to the target gene of the pathogen causing powdery mildew resulted in lowered disease severity in rubber.

- **Nanocarrier-Mediated Gene Silencing (NDGS):** One of the major drawbacks of RNA-based biopesticides is the rapid degradation of dsRNA, where nanotechnology can help overcome this challenge. The layered double hydroxides (LDH), chitosan nanoparticles, clay nanosheets, silica nanoparticles, and single-walled carbon nanotubes (SWCNTs) have been studied for RNA delivery and confer their protective properties to enhance the persistence of RNA and the efficiency of silencing. For instance, single-walled carbon nanotubes (SWNTs) enter cell walls and avoid degradation of biomolecules within cells, and are effective cargo transporters into living plant cells when introduced by whitefly and diamondback moth. Clay-based formulations, such as BioClay™, also have been studied to deliver dsRNA to plant viruses within the crops of vegetable plants such as zucchini and capsicum.
- **Microbial-mediated gene silencing:** Engineered microorganisms or insect-associated symbionts can produce or protect dsRNA to achieve more persistent delivery. The symbiotic bacteria can also be continually cultured and provide dsRNA, which greatly improves the efficiency of RNAi. For example, an RNAi biological pesticide platform technology developed by Renaissance BioScience Corp involves the delivery of dsRNA in baker's yeast, which will be sprayed onto the surface of crops to have its effect on Colorado potato beetle and other chewing pests.
- **Extracellular Vesicles:** Plant and microbial EVs are nature's RNA couriers and can be used as biological cargo carriers to protect dsRNA and transport, providing a new method for targeted RNA delivery in the future.

RNAi Technology in Commercial Action

As of 2025, four dsRNA-based crop-protection products had been registered, including three plant-incorporated dsRNA maize products (SmartStax PRO®, MON95275, DP23211) for the control of corn rootworm. Another important milestone for sprayable RNA biopesticides is Calantha™ contain the dsRNA active ingredient Ledprona for control of Colorado beetle in potato.

Challenges in RNAi Technology

Although RNA-based biopesticides have the potential to be very specific in protecting crops, the efficacy of the products depends on delivery requirements, stability issues, and biological barriers:

- Externally applied dsRNA can rapidly degrade due to UV radiation, rainfall, and temperature changes.
- dsRNA is not very stable at low pH or in the environment, which decreases the quantity of the intact RNA that reaches the target.
- dsRNA is broken down by digestive nucleases and other digestive enzymes before it can get to the target cells in the insect gut.
- Careful selection of sequences with minimal similarity to genes in beneficial and non-target organisms is essential for effective RNAi.
- Traditional foliar sprays may be ineffective for retaining and penetrating waxy leaves or during rainfall. An optimized formulation should include RNA protection, adhesion, controlled release and efficient uptake without causing phytotoxicity.
- The high cost of production can be incurred on large-scale synthesis, purification, formulation and storage of high-quality dsRNA.
- RNA-based products need to be evaluated from a regulatory perspective for environmental fate, persistence and food safety.

Conclusion and Future Perspectives

In the near future, it is not expected that RNAi will replace conventional chemical pesticides. Rather, it is probably to be a key element of integrated precision-based crop protection. Great potential lies in the combination of sequence-specific RNAi and biological control agents, resistant cultivars, beneficial microorganisms, pheromone approaches, and smart farming technologies. Future development of nanotechnology, target selection using artificial intelligence, precision spraying and controlled-release formulations holds promise to further enhance stability and field performance of dsRNA. In parallel, enabling policies, regulatory pathways, affordable production, and farmer awareness will be key for the scaling-up process. The future of crop protection is not RNAi versus chemicals, but RNAi combined with biology and smart technologies for residue-free crop protection and sustainable agriculture.

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"Physiological Disorders in Cauliflower: A Comprehensive Review of Causes, Symptoms and Management Strategies"

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Introduction

Cauliflower (Brassica oleracea var. botrytis) is a thermo-sensitive cole crop whose vegetative growth, curd initiation, and subsequent curd development are strongly influenced by environmental conditions. Thompson and Kelly (1957) reported that cauliflower is among the most temperature-responsive cole crops, with departures from the optimum temperature range potentially causing substantial deterioration in curd development and quality. Besides insect pests and pathogenic diseases, the crop is affected by a range of physiological disorders that can adversely influence curd formation, size, appearance, market value, and overall productivity. Unlike infectious diseases, these disorders are non-pathogenic in origin and are generally associated with fluctuations in temperature, nutritional deficiencies or imbalances, inadequate or excessive soil moisture, unsuitable planting dates, varietal susceptibility, and mechanical or other environmental stresses. The occurrence and severity of these abnormalities are largely governed by complex genotype x environment interactions, particularly during the critical stages of curd initiation and development (Nonnecke et al., 1989). Since cauliflower has a narrow temperature range for optimum curd formation, exposure to unfavorable temperatures, even for relatively short periods, may produce persistent and sometimes irreversible defects in curd quality. The major physiological disorders reported in cauliflower include buttoning, riciness, fuzziness, whiptail, hollow stem, browning of curd, blindness, leafiness or bracting, multiple curds, pinking, chlorosis, tip burn, and black speck. The following section provides a detailed account of these disorders, with emphasis on their symptoms, causal factors, predisposing conditions, and appropriate management practices.

1. Buttoning

Symptoms:- Buttoning is characterized by the **premature formation of small, compact curds** before the plant has developed sufficient foliage to support the production of a normal marketable head. The buttons remain small, exposed and poorly developed, and the plants generally possess a restricted leaf canopy (NHB, 2008).

Causes:- The disorder results from **premature curd initiation associated with restricted vegetative growth**. Important causes include inadequate nitrogen supply, transplanting of over-aged seedlings, transplanting shock, unsuitable planting dates, moisture stress, unfavorable temperatures, poor soil conditions, inappropriate planting time, cultivar susceptibility, and pest or disease damage, and unfavorable temperature conditions (NHB, 2008).

Management:- Buttoning can be effectively reduced by using **healthy, vigorous, appropriately aged transplants** and minimizing transplanting shock. Adequate and uniform soil moisture should be maintained, while balanced nutrition-particularly sufficient nitrogen-should be ensured to support adequate vegetative growth. Cultivars should be selected according to their adaptation to the prevailing temperature conditions, and sowing and transplanting should be timed so that curd initiation occurs under favorable environmental conditions.

2. Riceyness

Symptoms:- Riceyness or riciness, is characterized by an uneven, coarse and granular curd surface. Individual floral units elongate and become distinctly separated, producing an appearance resembling grains of rice. The curd becomes loose rather than compact, resulting in reduced market quality (VRI- Vegetable Research Institute, 2016).

Causes:- Riceyness is primarily associated with unfavorable temperature during curd development**,** particularly temperatures above the optimum for the cultivar, resulting in a loose, coarse, and rice-like curd with reduced market quality. Temperature fluctuations and rapid reproductive development can aggravate the disorder, (VRI- Vegetable Research Institute, 2016).

Management:- Cultivars should be selected according to their temperature adaptation. Planting should be timed so that the period of curd development coincides with favorable temperatures. Excessive nitrogen and other practices that promote excessively rapid growth should be avoided, and curds should be harvested at the appropriate maturity stage (VRI- Vegetable Research Institute, 2016).

3. Fuzziness or Fuzzy Curd

Symptoms:- Fuzziness is characterized by a velvety or fuzzy appearance of the curd**.** The individual flower pedicels elongate and become visible, producing an irregular, soft-textured surface instead of a dense and compact curd. Fuzziness is recognized as a commercially undesirable quality defect in cauliflower. (AMS USDA, 2017)

Causes:- The disorder is associated with unfavorable environmental conditions during curd development**,** Rapid curd development, poor-quality seed, and environmental stress during reproductive growth may further increase the severity of the disorder, resulting in elongated floral structures and a loose, fuzzy curd**.** particularly temperature conditions outside the optimum range of the cultivar. Genetic susceptibility may also influence its expression.

Management:- Use cultivars adapted to the local production season and select high-quality seed. Planting should be scheduled so that curd formation occurs under favorable temperature conditions. Balanced nutrition and uniform crop growth should be maintained.

4. Whiptail

Symptoms:- Whiptail is a characteristic molybdenum-deficiency disorder**.** Young leaves develop marginal chlorosis and may become pale or almost white. Leaf blades fail to expand normally, and under severe deficiency only the midrib may develop, producing a characteristic whip-like structure. Severe deficiency can deform or kill the growing point and prevent normal curd formation (NHB, 2008).

Causes:- The primary cause is inadequate availability of molybdenum (Mo)**.** Mo availability decreases markedly in acidic soils, and whiptail is particularly common when soil pH is below approximately 5.5 (NHB, 2008).

Management:- Soil pH should be determined before corrective treatment. Liming acidic soils can increase Mo availability. Where deficiency is confirmed, molybdenum should be supplied according to soil-test and locally recommended rates. Because Mo has a narrow range between adequate and excessive concentrations, indiscriminate application should be avoided (NHB, 2008).

5. Hollow Stem

Symptoms:- Hollow stem is characterized by formation of a longitudinal cavity within the stem**,** which may sometimes extend toward the curd. Internal tissues may show brown or water-soaked discoloration. In some plants the stem is hollow without obvious external symptoms, making longitudinal sectioning necessary for diagnosis (Utah State University Extension, 2017).

Causes:- Hollow stem has traditionally been associated with boron deficiency, particularly when accompanied by brown internal tissue. However, the disorder is not exclusively nutritional: excessive nitrogen and very rapid growth can also contribute to cavity formation. Research indicates that hollow stem is a complex trait and that boron deficiency does not explain every occurrence (PubMed Central, PMC, 2019).

Management:- Balanced fertilization and uniform plant growth should be maintained. Excess nitrogen should be avoided, while boron should be supplied only when deficiency is confirmed by appropriate soil or tissue testing. Irrigation should be managed to prevent severe moisture fluctuations (Utah State University Extension, 2017).

6. Browning of Curd

Symptoms:- Browning initially appears as water-soaked areas on the stem or curd, which subsequently become brown, rusty-brown or pinkish. Internal stem tissues may become discolored and the stem may develop a hollow cavity. In severe boron deficiency, affected curds may have an undesirable or bitter taste (NHB, 2008).

Causes:- Browning is strongly associated with boron deficiency. Boron is important for normal meristem and cell-wall development, and inadequate availability can result in abnormal stem and curd tissues (NHB, 2008).

Management:- Soil and plant analysis should be used to confirm boron deficiency. Where deficiency is established, boron should be applied at locally recommended rates. Uniform soil moisture and balanced fertilization should be maintained. Care should be taken because excessive boron can itself become toxic (NHB, 2008).

7. Blindness

Symptoms:- Blindness occurs when plants fail to develop a normal terminal curd. Affected plants may produce large, dark-green, thick and leathery leaves but lack a marketable head. The growing point may be damaged or fail to develop normally (Utah State University Extension, 2017).

Causes:- Blindness has been associated with low-temperature stress and injury to the growing point. Insect injury or other post-transplanting stresses can also destroy or impair the terminal growing point (Salter, P. J., 1957).

Management:- Plants should be handled carefully during transplanting and intercultural operations to protect the growing point. Appropriate planting dates and cultivars should be selected to minimize exposure to damaging temperatures, and pests affecting the growing point should be managed promptly.

8. Leafiness or Bracting

Symptoms:- Leafiness or bracting is characterized by the development of small green leaves or bracts through the cauliflower curd. These structures disrupt the normal white, compact appearance of the head and substantially reduce market quality (Utah State University Extension, 2017).

Causes:- The disorder represents a reversion toward vegetative growth during curd development. High temperatures, water stress and excessive nitrogen can promote the development of leaves within the curd (Utah State University Extension, 2017).

Management:- Planting should be scheduled so that curd formation occurs under favorable temperatures. Uniform soil moisture should be maintained and excessive nitrogen avoided.

Cultivars adapted to local climatic conditions should be preferred (Utah State University Extension, 2017).

9. Pinking of Curd

Symptoms:- Pinking is characterized by pink, reddish or purplish discoloration of portions of the curd. The abnormal pigmentation reduces the visual quality of the otherwise white curd.

Causes:- Pinking is associated with environmental conditions that stimulate accumulation of anthocyanin pigments. Genotype and environmental conditions influence the intensity and occurrence of the disorder. Pinking is included among the recognized physiological disorders of cauliflower (Think India Quarterly, 2019).

Management:- Cultivars with good curd coverage should be selected where the disorder is common. Appropriate planting dates, adequate irrigation and protection of developing curds from excessive environmental stress can reduce its occurrence.

Integrated Management of Physiological Disorders

Physiological disorders of cauliflower are best managed through preventive crop management, because many disorders originate before symptoms become visible. The most important measures include:

- **Appropriate cultivar selection-** Cultivars should be selected according to maturity group, temperature adaptation and local production season. Genotypic differences strongly influence susceptibility to disorders such as buttoning, riciness and fuzziness.
- **Correct planting time-** Planting dates should be adjusted so that vegetative growth and curd development occur under favorable temperature conditions. This is particularly important for buttoning, riciness, fuzziness, bracting and other curd abnormalities (VRI,Vegetable Research Institute, 2016).
- **Balanced nutrient management-** Nitrogen should be supplied adequately but not excessively. Soil testing should be used to identify deficiencies of boron, molybdenum and other nutrients. Boron deficiency is particularly associated with browning and hollow stem, whereas molybdenum deficiency causes whiptail (NHB, 2008).
- **Uniform soil moisture-** Both drought and excessive moisture can interfere with normal growth and nutrient uptake. Maintaining relatively uniform soil moisture is particularly

important for reducing buttoning, bracting and tip burn(Utah State University Extension, 2017).

- **Protection of the growing point-** Mechanical damage and insect injury to the terminal growing point should be minimized because such injury can contribute to blindness and multiple-curd formation.Soil pH management - Soil pH should be monitored regularly. Maintaining suitable pH is particularly important for molybdenum availability and prevention of whiptail in acidic soils (NHB, 2008).
- **Timely harvesting-** Cauliflower should be harvested at the appropriate maturity stage. Delayed harvest can increase curd deterioration and quality defects, including excessive opening, bracting and other undesirable changes.

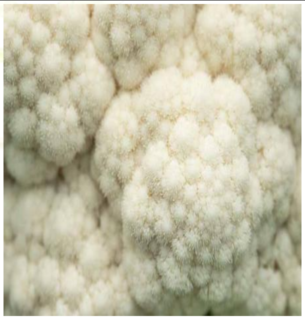
Conclusion

Physiological disorders represent an important but frequently underestimated constraint to cauliflower production. Disorders such as buttoning, riciness, fuzziness, whiptail, hollow stem and browning directly affect curd development and marketable quality, whereas blindness, bracting, pinking, multiple curds, chlorosis, tip burn and black speck further contribute to yield and quality losses. Their development is governed by complex interactions among temperature, cultivar, nutrient availability, soil pH, moisture status and crop-management practices. Consequently, successful management depends primarily on prevention through appropriate cultivar selection, correct planting time, balanced nutrition, adequate irrigation, protection of the growing point and maintenance of suitable soil conditions.

All Physiological Disorders in Cauliflower


Buttoning

Riceyness


Fuzziness

 **Whiptail**	 **Hollow Stem**	 **Browning of Curd**
 **Blindness**	 **Leafiness or Bracting**	 **Pinking of Curd**

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Khet Bachao Abhiyan: Movement to Protect Farmers and Revitalize Indian Agriculture

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The *Khet Bachao Abhiyan* is also referred to as *Kheti Bachao Abhiyan*. It is a nationwide initiative. It aims at promoting sustainable agriculture and improving soil health through scientific and community-driven approaches.

Agriculture is the backbone of India's economy. It provides livelihood to millions of people and ensuring our food security. In recent years, it has been observed that farmers have been facing increasing challenges like climate change, declining soil health, rising costs and uncertain markets. In this backdrop the *Khet Bachao Abhiyan* or Save Farming Campaign emerged as an important initiative. Its aim is to protect farmers and preserving agriculture.

The Genesis

The campaign received further momentum when it was formally highlighted at the national level, with efforts led by the Government of India and scientific institutions. This is as per the recent reports, including those from policy and media sources. The initiative has been linked with broader national goals of sustainable agriculture and soil conservation.

Khet Bachao Abhiyan is not formed by merging any existing programmes. It is an independent campaign. It works in convergence with various ongoing agricultural initiatives. Rather than replacing or restructuring them it complements these programmes by strengthening awareness and participation,

Khet Bachao Abhiyan or Save Farming Campaign was not introduced as a typical government scheme. It has emerged as a collective effort by farmer organizations, civil society groups, and agricultural stakeholders. During 2020–2021, the Khet Bachao Abhiyan has gained prominence due to the widespread farmer mobilizations. The campaign was announced with the broader aim to focus on the agrarian distress and to unite farmers across the country. It has provided a platform through which farmers can express their concerns regarding various issues like agricultural policies, market uncertainties, livelihood risks etc.

Thus, the background of the campaign lies in the structural problems of Indian agriculture. Farmers in India are mostly small and marginal. Moreover, they possess fragmented land which makes it difficult to achieve economies of scale. Further issues like rising input costs, unpredictable weather patterns and fluctuating crop prices increase their vulnerability. During that time the introduction of new agricultural reforms has added more anxiety among the farmers. It has prompted them to raise a unified voice. It thus has emerged as a response to these urgent challenges. With the growing concerns of soil degradation in India, the need for this campaign has been further emphasized. Excessive and imbalanced use of chemical fertilizers over the years has resulted in declining of soil fertility and productivity. Many regions are facing issues such as nutrient deficiency, reduced organic matter, and environmental stress. In this regard, the Khet Bachao Abhiyan aims to restore soil health and promote sustainable farming practices. Recent reports, including those from policy and media sources, indicate that the campaign received further momentum when it was formally highlighted at the national level, with efforts led by the Government of India and scientific institutions. The initiative has been linked with broader national goals of sustainable agriculture and soil conservation.

Its Nature and Functions

The *Khet Bachao Abhiyan* operates more as a movement-driven programme rather than formal government schemes. Activities under this campaign include village-level meetings, awareness drives, rallies and training sessions. It also emphasises on discussions aimed at educating farmers about their rights as well as available support systems. Overall, it focuses on awareness creation, farmer mobilization and policy advocacy. The programme is implemented through several key components. The key components are soil testing campaigns, promotion of balanced fertilizer use, adoption of organic and natural farming practices, and efficient water management techniques. Field demonstrations and farmer training sessions are conducted. The aim is to encourage practical learning and adoption of improved agricultural methods.

The programme also promotes balanced fertilizer use, organic farming and soil conservation practices for sustainable agriculture. It encourages farmers to come together through cooperatives and Farmer Producer Organizations (FPOs). Which can help them access better markets and improve their bargaining power. In short, the campaign acts as a bridge between farmers and policymakers. It ensures that grassroots issues are heard and addressed.

Aims and Vision

The central aim of the *Khet Bachao Abhiyan* is to protect the livelihood of farmers as well as to ensure the long-term sustainability of agriculture. It emphasizes the need for fair and remunerative prices for crops, primarily through MSP (Minimum Support Price). The campaign also seeks to reduce farmer indebtedness and strengthen food security in the country. Further, it also promotes environmentally sustainable practices.

Focussing on policy advocacy is another important aspect of the campaign. It aims to influence agricultural policies by bringing farmers together, in a way that benefits small and marginal farmers. These small and marginal farmers form the majority of the farming community in India.

Target Beneficiaries of the Programme

The campaign primarily targets small and marginal farmers, who are the most vulnerable to economic and environmental challenges. It also includes tenant farmers, sharecroppers, agricultural labourers, and women farmers, whose contributions often go unnoticed. By addressing the needs of these groups, campaign create a more inclusive and equitable agricultural system. A stronger agricultural sector ensures food availability and stable prices. Thus, the benefits extend to rural communities and consumers as well.

Area Coverage and Reach

The *Khet Bachao Abhiyan* has a nationwide presence. It has active participation from several major agricultural states such as Punjab, Haryana, Uttar Pradesh, Rajasthan, Maharashtra, and West Bengal. The campaign functions at multiple levels. Starting from villages it extends to district, state, and even national levels.

It has a decentralized approach, which allows it to address region-specific issues, like irrigation challenges, soil degradation, or market access problems. This flexibility makes the campaign more relevant and effective across diverse agricultural regions of the country. The campaign has achieved a significant scale, reaching more than 2.7 crore farmers across the country.it was done through awareness drives, training programmes, and field-level interventions. This highlights its acceptance and impact at the grassroots level.

Funding and Institutional Support

The *Khet Bachao Abhiyan's* funding pattern is one of its unique aspects. Like a typical government scheme, it is not backed by a separate dedicated budget. It draws support from existing agricultural programmes, institutional resources, and extension systems. Agricultural departments, research institutions local governance etc like organisations contribute to its implementation.

An important role in this initiative is played by Indian Council of Agricultural Research (ICAR). It has provided the technical guidance and research support. Through its network of Krishi Vigyan Kendras (KVKs) and agricultural scientist. The campaign ensures that farmers receive scientifically validated information and practical solutions.

The campaign makes effective use of various existing infrastructure, including Krishi Vigyan Kendras (KVKs), agricultural universities and extension workers. This integrated approach ensures that resources are utilized efficiently. which lessens the need for additional financial burden.

Key Developments So Far

The *Khet Bachao Abhiyan* has made significant progress since its inception. It has improved both the outreach and awareness among people. It has conducted plenty of awareness camps, training programmes, and field demonstrations across the regions. These activities have helped the farmers to understand better farming practices. It has introduced the concept of soil health management and the importance of sustainable agriculture among the farmers.

Mass media and digital platforms have also been widely used to spread its messages and has reached millions of people. It has created a broader understanding of farmers' issues and the importance of agriculture in national development.

Significance and Advantages of the Campaign

One of the biggest strengths of the *Khet Bachao Abhiyan* is its ability to unite farmers. It amplifies their voices. It has increased awareness about agricultural policies and market conditions. It is enabling out farmers to make informed decisions. The campaign also promotes sustainable farming practices. which is essential for preserving natural resources and ensuring long-term productivity. It further, encourages the formation of farmer collectives. Which improves their access to markets and enhancing their income potential. The campaign contributes to social inclusion and empowerment by providing a platform to marginalized and vulnerable groups.

Issues and Limitations

Khet Bachao Abhiyan is not a formal government scheme. Its impact may vary across regions. Its success depends on local participation and support. The lack of a centralized structure often led to inconsistencies in implementation. Thus, despite its many strengths, the campaign faces certain limitations too.

The campaign no doubt is effective in raising awareness but translating this awareness into concrete policy changes or economic benefits can take time. Sustaining long-term engagement among farmers is also a challenge. Moreover, managing diverse interests within the movement is also very difficult.

Conclusion and Way Forward

The Khet Bachao Abhiyan also complements several ongoing agricultural initiatives. Like the initiatives focused on sustainability and climate resilience. It aligns with national priorities such as improving soil health, reducing input costs, and promoting environmentally friendly farming practices. By integrating awareness with action, the campaign serves as a bridge between policy and practice.

In conclusion, the *Khet Bachao Abhiyan* is a hope for Farmers and the Nation. It represents a powerful collective effort to protect agriculture. Further, it also attempts to improve the lives of the farmers. It promotes awareness, encourage sustainable practices, and advocate for fair policies. It thus, helps the farmers to navigate the complex challenges they face every day. It contributes to food security, environmental conservation, and balanced economic growth in the country.

This campaign has the potential to transform Indian agriculture into a more resilient, inclusive, and sustainable system. However, it requires strong supported and backing from institutions. It also demands active participation from all stakeholders. Finally, it can be concluded that saving farming is not only helping the farmers rather it is securing the future of the nation itself. Its long-term success will depend on continuous farmer participation. Its effective implementation, and the ability to translate awareness into measurable improvements in agricultural productivity and farmer income is very crucial.

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Protected cultivation of vegetable crops present status and prospects

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Abstract

Protected cultivation is a modern agricultural technology that provides favourable growing conditions for vegetable crops through structures such as greenhouses, polyhouses, shade-net houses, tunnels, and rain shelters. It improves crop productivity, quality, water and nutrient-use efficiency, and enables year-round and off-season production. Major vegetables grown under protected conditions include tomato, capsicum, cucumber, brinjal, lettuce, and leafy vegetables. In India, government programmes such as MIDH and NHB support the adoption of protected cultivation. However, high initial investment, technical requirements, and maintenance costs remain major constraints. Future developments in IoT, automation, hydroponics, aeroponics, artificial intelligence, and precision fertigation are expected to further improve the efficiency and sustainability of protected vegetable production.

Keywords: Protected cultivation, greenhouse, polyhouse, vegetable crops, fertigation, hydroponics.

1. Introduction

Protected cultivation refers to the production of crops within structures that provide a degree of control over environmental factors such as temperature, relative humidity, radiation, ventilation, irrigation and, in advanced systems, carbon dioxide concentration. The primary objective is to create a favourable microclimate that supports crop growth while reducing the effects of adverse environmental conditions.Protected cultivation has become an important component of modern horticulture because conventional open-field production is increasingly affected by climatic variability, extreme temperatures, irregular rainfall, pests and diseases.

By modifying the crop environment, protected structures can facilitate higher productivity, better produce quality and more reliable production schedules. Protected cultivation also provides opportunities for off-season vegetable production, when market prices may be favourable (Singh & Sirohi, 2006).The technology ranges from relatively simple low tunnels and shade-net structures to sophisticated climate-controlled greenhouses equipped with automated ventilation, cooling, fertigation and sensor systems. The selection of a structure depends on crop requirements, climatic conditions, investment capacity and the intended production system.

2. Types of Protected Cultivation Structures

2.1 Greenhouse/Polyhouse

A greenhouse or polyhouse is a framed structure covered with transparent or translucent material such as polyethylene, glass or polycarbonate. The covering permits solar radiation to enter while reducing the effects of adverse weather conditions.Temperature, humidity, ventilation, irrigation and nutrient supply can be managed according to crop requirements. Polyhouses are particularly suitable for high-value vegetables such as tomato, capsicum, cucumber, brinjal and lettuce.Protected structures can significantly modify the crop microclimate. In a study conducted in the hot-arid region of Rajasthan, cucumber grown under a naturally ventilated polyhouse exhibited better growth and yield than crops grown under insect-proof and shade-net houses (Khapte *et al*., 2021).

Suitable crops

- Tomato
- Capsicum
- Cucumber
- Brinjal
- Lettuce
- Leafy vegetables

2.2 Insect-Proof Net House

An insect-proof net house is covered with fine mesh that restricts the entry of insect pests while allowing air movement and light penetration. Such structures are useful for reducing insect-mediated disease transmission and can contribute to reduced pesticide use.

Suitable crops

- Tomato
- Chilli
- Capsicum
- Brinjal
- Cucumber
- Leafy vegetables

2.3 Shade-Net House

A shade-net house is covered with shade material that reduces solar radiation and crop temperature. Shade levels can be selected according to crop requirements.

It is particularly useful in regions with high solar radiation and for crops or nursery plants that are sensitive to excessive heat and light.

Suitable crops

- Leafy vegetables
- Coriander
- Nursery plants
- Shade-tolerant horticultural crops

2.4 Low Tunnel

Low tunnels are small structures constructed over crop rows using hoops covered with polyethylene or other protective materials. They are relatively inexpensive and are useful for protecting young plants from low temperatures, frost, wind and adverse weather.

Suitable crops

- Cucumber
- Melon
- Watermelon
- Pumpkin
- Other cucurbits

Low tunnels are particularly useful for off-season vegetable production and can provide an economical form of protected cultivation (Singh & Sirohi, 2006).

2.5. Walk-In Tunnel or High Tunnel

Walk-in tunnels are taller structures that allow workers to enter the structure for irrigation, training, harvesting and other crop-management activities. They generally have a lower investment requirement than sophisticated climate-controlled greenhouses. They are suitable for vegetables such as tomato, cucumber, capsicum, leafy vegetables and nursery crops.

2.6 Row Covers

Row covers consist of lightweight plastic or fabric materials placed directly over crop rows. They provide protection from low temperature, wind and certain insect pests.

Suitable crops

- Cabbage
- Cauliflower
- Radish
- Carrot
- Other short-duration vegetables

2.7 Rain Shelter

Rain shelters consist primarily of a protective roof that prevents direct contact of rainfall with the crop while maintaining natural ventilation. They can be useful in regions receiving heavy or prolonged rainfall.

Suitable crops

- Tomato
- Capsicum
- Chilli
- Other vegetables sensitive to excessive rainfall

3. Greenhouse Construction Materials

The structural components of a greenhouse generally include galvanized iron (GI) pipes, polyethylene covering, insect-proof nets, shade nets, ventilation systems, drip irrigation and fertigation equipment.

Component	Typical specification	Purpose
GI column	60 mm OD × 2 mm thickness	Main structural support

Component	Typical specification	Purpose
GI arch/rafter	48 mm OD × 2 mm	Roof support
GI purlin	32 mm OD × 2 mm	Roof structural support
GI bracing	25 mm OD × 2 mm	Structural stability
Polyethylene film	UV-stabilized, approximately 200 µm	Covering material
Insect-proof net	40–50 mesh	Pest exclusion
Shade net	35–75% shade	Reduction of solar radiation
Cooling pad	Approximately 100–150 mm	Evaporative cooling
Exhaust fan	Approximately 36–50 inch	Ventilation
Drip lateral	Approximately 16 mm	Irrigation/fertigation
Main pipe	50–63 mm	Water distribution
Sub-main	32–40 mm	Water distribution
Spring wire	Approximately 2 mm	Fixing covering material
Lock channel	Approximately 1.5–2 mm	Securing polyethylene film

The precise dimensions should be selected according to the structural design, local climate, wind load, crop, covering material and applicable engineering standards rather than treating the above values as universal specifications.

4. Classification of Greenhouses

Greenhouses can be classified according to their structural design, shape, purpose and climatic suitability.

4.1 Lean-to greenhouse

A lean-to greenhouse is attached to an existing building or supporting structure. It is generally suitable for small-scale production, nurseries and home gardens.

4.2 Even-span greenhouse

The roof slopes are approximately equal on both sides. This design is commonly used for commercial vegetable production.

4.3 Uneven-span greenhouse

The two roof slopes have different dimensions. This type can be adapted to specific climatic and topographic conditions.

4.4 Ridge-and-furrow greenhouse

Several greenhouse spans are joined together. This design is useful for large commercial production units.

4.5 Quonset or hoop greenhouse

The structure has a curved roof supported by hoops. It is comparatively simple and can be economical for low- to medium-cost protected cultivation.

4.6 Saw-tooth greenhouse

Saw-tooth structures contain roof openings that facilitate natural ventilation. They can be useful in warm climates where removal of hot air is important.

5. Standard Dimensions of Selected Greenhouse Types

Greenhouse type	Typical width	Typical length	Approximate height
Even-span	5–9 m	20–30 m	2.5–4.3 m
Uneven-span	5–9 m	20–30 m	2.5–4.0 m
Ridge-and-furrow	6–9 m/span	30–100 m	4–6 m
Quonset/hoop	4–8 m	20–30 m	2.5–3.5 m
Lean-to	3–6 m	10–20 m	2.5–4.0 m
Saw-tooth	6–9 m	30–100 m	4–6 m

These dimensions are indicative rather than mandatory. Actual dimensions should be determined according to engineering requirements, site conditions and the specific crop-production system.

6. Role of Protected Cultivation in Vegetable Production

Protected cultivation provides several important advantages over conventional open-field cultivation.

6.1 Higher productivity

Protected structures allow growers to maintain a more favourable microclimate. Temperature, humidity, radiation and water supply can be managed to improve photosynthesis, flowering, fruit set and crop growth. Research on cucumber under hot-arid conditions demonstrated that naturally ventilated polyhouse cultivation produced substantially higher yield than insect-proof and shade-net structures (Khapte *et al*., 2021).

6.2 Off-season production

Protected cultivation allows vegetables to be produced outside their normal growing season. This can provide access to premium markets and potentially improve farm profitability.

6.3 Improved quality

Controlled environmental conditions can improve fruit size, colour, shape, firmness and marketable yield.

6.4 Efficient water and nutrient use

Drip irrigation and fertigation deliver water and nutrients directly to the root zone. This reduces unnecessary water application and allows more precise nutrient management.

6.5 Reduced pest pressure

Insect-proof structures can physically restrict pest entry, while controlled environments may reduce disease pressure. Consequently, pesticide applications may be reduced when integrated pest-management practices are properly implemented.

6.6 Climate resilience

Protected structures provide partial protection against heavy rain, wind, frost, excessive solar radiation and temperature extremes. This makes them useful tools for adapting vegetable production to climatic variability.

7. Protected Cultivation and Microclimate Management

The principal advantage of a protected structure is its ability to modify the crop microclimate. Important environmental factors include:

- Temperature
- Relative humidity
- Solar radiation
- Air movement
- Root-zone temperature
- Soil/substrate moisture
- Nutrient concentration
- Carbon dioxide concentration

For example, Khapte *et al*., (2021) reported that naturally ventilated polyhouse conditions modified temperature, relative humidity and radiation in cucumber, resulting in improved crop performance compared with insect-proof and shade-net structures.

Advanced greenhouses use fans, evaporative cooling pads, ventilation openings, heating systems, shade screens and sensors to maintain environmental conditions within an appropriate range.

8. Irrigation and Fertigation

Efficient irrigation is essential in protected vegetable production. Drip irrigation is commonly used because it provides water directly to the root zone and minimizes evaporation and runoff. Fertigation combines irrigation with fertilizer application. It permits frequent and precise delivery of nutrients according to crop growth stage. Protected cultivation can therefore improve water and fertilizer-use efficiency when irrigation scheduling, substrate moisture and nutrient concentration are appropriately monitored.

9. Hydroponics and Aeroponics

Modern protected cultivation increasingly incorporates soilless production systems.

Hydroponics

Hydroponics involves growing plants without conventional soil, using a nutrient solution supplied to the root zone. It can be particularly useful where land or soil quality is limiting.

Aeroponics

Aeroponics involves suspending plant roots in an enclosed environment and delivering nutrients through a fine mist. It offers efficient use of water and nutrients but requires greater technical control and reliable equipment.The current MIDH guidelines explicitly promote newer components including hydroponics, aeroponics, soil replacement and sensor-based automation for fertigation.

10. Government Support for Protected Cultivation in India

Government programmes have played an important role in promoting protected horticulture in India. The Mission for Integrated Development of Horticulture (MIDH) supports protected cultivation activities including greenhouses, shade-net houses, rain shelters, plastic tunnels and anti-bird/anti-hail nets. The programme also includes modern components such as hydroponics, aeroponics and sensor-based fertigation automation. The National Horticulture Board (NHB) also provides financial assistance under its relevant horticultural development schemes, subject to prevailing guidelines, eligibility requirements, project size and approved cost norms. Current NHB guidance should be consulted because assistance provisions and technical requirements can be revised. Therefore, subsidy percentages should not be presented as universally fixed figures without specifying the particular scheme, component, beneficiary category and year of the guideline.

11. Present Status of Protected Cultivation in India

Protected cultivation has developed considerably in India, particularly in regions where high-value vegetable production, peri-urban horticulture and off-season production are economically attractive. Tomato, capsicum, cucumber, chilli, brinjal, lettuce and leafy vegetables are among the important crops cultivated under protected conditions.States with substantial adoption include parts of Maharashtra, Karnataka, Gujarat, Tamil Nadu, Punjab, Haryana, Himachal Pradesh and Rajasthan. Adoption is influenced by climate, availability of markets, access to infrastructure, technical knowledge and government assistance.Protected cultivation is particularly relevant to regions where high temperatures, excessive rainfall, frost or pest pressure restrict open-field production.

12. Protected Cultivation in Chhattisgarh

Chhattisgarh has considerable potential for protected vegetable production because of its expanding horticultural sector, increasing urban demand and opportunities for producing high-value vegetables.Protected cultivation can help Chhattisgarh farmers produce high-value vegetables during favourable market windows while protecting crops from excessive rainfall, temperature fluctuations and pest pressure.However, successful expansion requires appropriate structure selection, farmer training, quality planting material, irrigation infrastructure, reliable electricity, technical support and strong market linkages.

13. Present Status of Protected Cultivation Worldwide

Protected cultivation is widely practiced in countries including China, Spain, Japan, South Korea, Turkey, Italy, the Netherlands and the United States. China has developed an especially large protected horticulture sector, while European countries such as the Netherlands have developed highly sophisticated greenhouse systems incorporating automation, climate control, hydroponics and precision production.

Modern international greenhouse production increasingly integrates:

- Automated climate control
- Hydroponics

- Sensor-based irrigation
- Artificial intelligence
- Robotics
- LED lighting
- Automated fertigation
- Computer-based crop monitoring
- Renewable energy

The comparison of protected cultivation area among countries should be made cautiously because definitions and reporting methods differ between sources and years.

14. Production of Major Vegetable Crops under Protected Cultivation

The following values may be used as indicative production parameters, but actual plant density and yield vary with cultivar, greenhouse design, climate, training system, fertigation programme and management.

Crop	Example cultivar/hybrid	Spacing	Indicative yield under protected cultivation
Tomato	Arka Rakshak	45 × 45 cm	120–180 t/ha
Capsicum	Indra	45 × 45 cm	80–120 t/ha
Brinjal	Arka Navneet	60 × 45 cm	100–120 t/ha
Cauliflower	Pusa Snowball K-1	45 × 45 cm	25–35 t/ha
Cabbage	Pusa Mukta	45 × 45 cm	40–60 t/ha
Chilli	Indam-5	45 × 45 cm	80–100 t/ha
Lettuce	Grand Rapids	25 × 25 cm	25–35 t/ha
Spinach	All Green	Close spacing	~30 t/ha
Coriander	Gujarat Coriander-2	Close spacing	8–12 t/ha
Cucumber	Terminator/other hybrids	40 × 40 cm	150–200 t/ha

Crop	Example cultivar/hybrid	Spacing	Indicative yield under protected cultivation
Bottle gourd	Pusa Navin	200 × 60 cm	40–60 t/ha
Watermelon	Sugar Baby	100 × 60 cm	50–70 t/ha
Bitter gourd	Priya	100 × 60 cm	25–35 t/ha

These figures should be treated as indicative package-of-practice values rather than guaranteed yields.

15. Economics and Major Constraints

Although protected cultivation can increase productivity and enable premium production, it also requires greater capital and technical management than conventional farming.

Major advantages

1. Higher productivity per unit area.
2. Off-season production.
3. Improved quality and uniformity.
4. Better water and fertilizer-use efficiency.
5. Partial protection against adverse weather.
6. Potential reduction in pesticide use.
7. Better opportunities for high-value vegetable production.
8. Possibility of year-round production.

Major constraints

1. High initial investment.
2. High cost of repair and maintenance.
3. Requirement for skilled labour.
4. Dependence on reliable irrigation and electricity.
5. Technical complexity in advanced structures.
6. Requirement for quality planting material.
7. Pest and disease outbreaks can spread rapidly in enclosed environments.
8. Market-price fluctuations.

9. Limited cold-chain and post-harvest infrastructure.
10. Difficulty in accessing technical assistance in some rural areas.

16. Future Prospects

The future of protected vegetable cultivation lies in combining conventional greenhouse technology with digital agriculture and resource-efficient production systems.

16.1 Smart greenhouses

Sensors can continuously monitor temperature, humidity, light, substrate moisture and nutrient conditions. Automated systems can then adjust ventilation, irrigation and fertigation.

16.2 IoT-based monitoring

Internet-connected sensors can allow farmers to monitor greenhouse conditions remotely and receive alerts when temperature, humidity or irrigation conditions become unsuitable.

16.3 Artificial intelligence

Artificial intelligence can support disease detection, yield prediction, irrigation scheduling and optimization of greenhouse climate.

16.4 Automation and robotics

Automation can reduce labour requirements for irrigation, fertigation, harvesting, crop monitoring and climate management.

16.5 Hydroponics and aeroponics

Soilless systems are likely to expand in areas with limited land or poor soil conditions. The inclusion of hydroponics and aeroponics in current MIDH guidelines demonstrates the policy interest in these technologies.

16.6 Renewable energy

Solar-powered pumps, sensors, cooling systems and greenhouse equipment could reduce dependence on conventional electricity and improve sustainability.

17. Conclusion

Protected cultivation is an important technology for increasing the productivity, quality and reliability of vegetable production. Greenhouses, polyhouses, shade-net houses, insect-proof net houses, tunnels and rain shelters create favourable microclimates that allow farmers to reduce the impact of adverse environmental conditions and produce high-value vegetables more efficiently.Scientific evidence indicates that the choice of protected structure has a substantial influence on crop microclimate and productivity. For example, naturally ventilated polyhouse conditions produced markedly better cucumber performance than insect-proof and shade-net structures under hot-arid conditions (Khapte *et al*., 2021). In India, government programmes such as MIDH provide support for protected structures and are increasingly incorporating hydroponics, aeroponics and sensor-based automation. Nevertheless, high capital requirements, technical complexity, energy costs, skilled-labour requirements and market constraints continue to limit adoption.The future of protected vegetable cultivation will depend on integrating greenhouse technology, precision irrigation, fertigation, IoT sensors, automation, artificial intelligence, hydroponics, renewable energy and improved market linkages**.** With appropriate technical training, affordable structures and effective government support, protected cultivation can contribute substantially to higher farmer income, efficient resource use, climate resilience and food and nutritional security.

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MICRO GREENS: PRODUCTION TECHNOLOGY, NUTRITIONAL VALUE AND COMMERCIAL POTENTIAL

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Abstract

Microgreens are young seedlings of vegetables, herbs, and grains harvested within 7–21 days of germination. They are rich in vitamins, minerals, carotenoids, phenolic compounds, antioxidants, and bioactive compounds such as glucosinolates (Sun *et al*., 2023; Liao *et al*., 2024). Varieties such as broccoli, red cabbage, kale, radish, amaranth, and beetroot can be grown in soil or soilless systems under controlled conditions. Vertical and hydroponic cultivation enables efficient use of space; one study reported a 6–10-fold increase in biomass within 10 days and about four-fold higher yield per m² than conventional cultivation (Tilahun *et al*., 2023). Optimized LED lighting can further improve growth, yield, and nutritional quality (Viršilė *et al*., 2023). Thus, microgreens have strong potential for sustainable food production and functional nutrition.

Keywords: Microgreens, nutritional value, LED lighting, urban farming, commercial potential

INTRODUCTION

The microgreens business is expanding rapidly, but it confronts a number of obstacles (Charlebois, 2019; Riggio *et al*., 2019). Microgreens are young, tender, edible seedlings of vegetables, herbs, or grains, typically harvested within 7–21 days after germination. Their rising popularity is also driven by a shift towards sustainable food systems and functional foods. Studies show that species like broccoli, red cabbage, and radish microgreens are rich in bioactive compounds such as glucosinolates, polyphenols, and carotenoids (Zhang *et al.,* 2023). Microgreens are a new class of edible vegetables (Pinto *et al*., a very specific type which includes seedlings of edible vegetables, ranging in size from 8 to 10 cm. (Xiao *et al*., 2012).

Microgreens: Cultivation, Nutritional Traits, Uses and Market Potential

Introduction

Microgreens are young, tender seedlings of vegetables, herbs, and grains that are harvested at an early stage of growth, usually within 7–21 days after germination. They are gaining popularity because of their high nutritional value, attractive appearance, distinctive flavors, and short production cycle. Microgreens can be cultivated in soil as well as soilless media such as coco peat, coconut coir, and perlite. Their ability to grow in limited spaces makes them suitable for home gardening, vertical farming, hydroponics, and commercial production.

Growing Process of Microgreens

Seed Selection and Variety Choice

Selecting good-quality seeds is the first step in successful microgreen production. Crops such as broccoli, cabbage, radish, mustard, beetroot, pea, amaranth, and spinach are commonly cultivated because of their rapid germination and nutritional value. Arugula, cilantro, and basil are also popular because of their distinctive flavors and health-promoting properties (Xiao *et al*., 2012).

Crop	**Seed rate (g/1020 tray)**
Broccoli	15–20
Cabbage	15–20
Beetroot	20–30
Radish	30–35
Mustard	10–15

Seed Soaking

Some larger seeds, particularly pea seeds, benefit from soaking before sowing. Seeds are generally soaked for approximately 4–12 hours depending on the crop. Soaking softens the seed coat, promotes water absorption, and can encourage faster and more uniform germination.

Selection of Growing Medium

Microgreens can be grown in soil or soilless substrates. Coco peat and coconut coir are commonly used because they are lightweight, retain adequate moisture, and provide good aeration for root development (Kyriacou *et al*., 2019). A shallow tray with good drainage is generally filled with approximately 2–3 cm of moist growing medium.

Sowing of Seeds

After soaking, seeds are evenly broadcast over the moist growing medium and gently pressed to ensure good contact. A thin layer of coco peat may be used to cover the seeds. The trays are then maintained under suitable moisture and environmental conditions to initiate germination (Mir *et al*., 2023).

Germination and Environmental Conditions

During germination, environmental conditions should be carefully controlled. Most microgreens germinate well at approximately 18–22°C, with relatively high humidity. Covering the trays during the initial germination period can help maintain moisture and encourage uniform sprouting (Xiao *et al*., 2012). Once germination occurs, adequate ventilation is important to reduce excessive humidity and the risk of fungal growth.

Lighting

After germination, microgreens require sufficient light for photosynthesis and healthy development. Generally, 12–16 hours of light per day is suitable for many microgreen crops. Artificial LED lighting can be used in indoor and vertical farming systems and may improve biomass production and nutritional quality when properly optimized (Kyriacou *et al*., 2016).

Water and Nutrient Management

Proper water management is essential for healthy microgreen production. The growing medium should remain moist but should not become waterlogged. Most microgreens have a short growth cycle and require relatively little fertilizer when grown in a suitable substrate. In hydroponic systems, nutrient solutions can supply essential mineral elements directly to the plants (Pinto *et al*., 2021; Mir *et al*., 2023).

Harvesting

Microgreens are generally ready for harvest **7**–21 days after germination, depending on the crop and growing conditions. Harvesting is commonly carried out when the cotyledons are fully developed and the first true leaves begin to appear. The plants are cut close to the growing medium using a clean, sharp knife or scissors to avoid damaging the harvested product (Xiao *et al*., 2012). Careful handling after harvest is important for maintaining freshness and quality.

Types of Microgreens and Nutritional Traits

Microgreens contain considerable amounts of vitamins, minerals, proteins, carotenoids, phenolic compounds, and other bioactive substances. Their nutritional composition varies according to species, cultivar, growing conditions, and harvest stage (Paradiso *et al*., 2023).

Crop	**Protein (%)**	**Important nutrients**	**Nutritional importance**
Broccoli	2.23–3.00	Vitamin C	Antioxidant activity and dietary health
Radish	1.81	Vitamin K	Supports bone health and normal blood clotting
Mustard	2.78	Vitamins A and C	Supports immune, eye, and skin health
Pea	4.03	Vitamin K	Important for bone health and blood clotting
Beetroot	2.09	Vitamins C and K	Supports immune and bone health
Amaranth	13–19	Minerals and bioactive compounds	Supports overall nutritional health
Spinach	Variable	Vitamins and minerals	Contributes to a balanced diet

Microgreens in Home and Commercial Production

Microgreens are increasingly cultivated in both homes and commercial farming systems because they require little space and have a short production period. At the household level, they can be grown indoors, on windowsills, balconies, or in small trays, providing a convenient source of fresh greens (Xiao *et al*., 2022; Poudel *et al*., 2021).

Commercially, microgreens are used in restaurants, salad mixes, fresh-food markets, and nutraceutical products because of their vibrant colors, distinctive flavors, and high concentration of nutrients and bioactive compounds (Kyriacou *et al*., 2021). Their short production cycle of approximately 7–21 days also makes them attractive for small-scale entrepreneurs and urban farms. Vertical and hydroponic systems can further increase production efficiency by making better use of limited growing space (Choe *et al*., 2022).

Market Value of Microgreens

The market value of microgreens varies according to crop, quality, location, production system, packaging, and consumer demand. Indicative retail values reported for selected microgreens are shown below.

Microgreen	Approximate market value	Pack size
Broccoli	₹150–300	100 g
Radish	₹100–250	100 g
Mustard	₹100–200	100 g
Pea	₹100–200	100 g
Beetroot	₹150–300	100 g

(Gupta et al., 2023)

Conclusion

Microgreens represent a promising component of sustainable agriculture because of their high nutritional value, rapid growth, short production cycle, and suitability for urban, vertical, and hydroponic farming. Their rich content of vitamins, minerals, antioxidants, and other bioactive compounds makes them valuable functional foods. They can be produced on a small scale at home or commercially using controlled-environment systems. Advances in LED lighting, vertical farming, hydroponics, and controlled-environment agriculture can further improve their productivity and nutritional quality. With increasing consumer awareness and demand for fresh and nutritious foods, microgreens have considerable potential to contribute to food security, economic opportunities, sustainable agriculture, and health-oriented food systems.

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INNOVATIVE POST HARVEST TECHNOLOGIES REDUSING LOSSES IN VEGETABLE CROPS

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Abstract

Vegetables are highly perishable commodities because of their high moisture content, high respiration rate, delicate tissues, and susceptibility to mechanical damage and microbial spoilage. Post-harvest losses occur throughout harvesting, handling, storage, transportation, and marketing, reducing the quantity, quality, nutritional value, and economic returns of vegetables. Innovative post-harvest technologies such as pre-cooling, cold-chain management, modified atmosphere packaging (MAP), controlled atmosphere (CA) storage, edible and nanocomposite coatings, and smart sensor systems can help slow respiration, moisture loss, ripening, and microbial deterioration. Pre-cooling methods such as room cooling, hydro-cooling, vacuum cooling, and ice cooling remove field heat soon after harvest and improve storage life. Cold-chain systems maintain appropriate temperature and humidity throughout storage and transportation, while MAP and CA regulate atmospheric gases to delay senescence. Nanotechnology provides additional opportunities through antimicrobial coatings, nanocomposite packaging, and nanosensors for monitoring storage conditions. These technologies can contribute to reducing food losses, maintaining quality, improving food security, and increasing the economic value of vegetable crops (Bai *et al*., 2023; Defraeye *et al*., 2023).

Keywords: Post-harvest losses, pre-cooling, cold chain, modified atmosphere packaging, controlled atmosphere storage, nanotechnology, vegetable crops.

1. Introduction

Vegetable crops are highly perishable agricultural commodities due to their high moisture content, high respiration rates, delicate tissues, and susceptibility to mechanical injury and microbial spoilage. Significant deterioration can occur between harvesting and consumption when vegetables are improperly harvested, handled, packaged, stored, transported, or marketed. These problems reduce freshness, nutritional quality, marketability, and economic returns.Traditional post-harvest practices are often insufficient to maintain vegetable quality for extended periods. Consequently, innovative technologies have become increasingly important for reducing losses and extending shelf life. These technologies include pre-cooling, refrigerated cold-chain management, controlled atmosphere storage, modified atmosphere packaging, edible coatings, active and intelligent packaging, nanotechnology, UV-C treatment, ozone treatment, cold plasma, and sensor-based monitoring systems.The effectiveness of these technologies depends on appropriate crop-specific temperature, humidity, atmospheric composition, packaging, and handling conditions. Their integration from harvesting through marketing can reduce deterioration and improve the efficiency and sustainability of vegetable supply chains (Bai *et al*., 2023).

2. Causes of Post-Harvest Losses

2.1 Physiological Losses

After harvesting, vegetables remain living tissues and continue to respire and lose water through transpiration. Continued respiration, ripening, senescence, and moisture loss can result in softening, wilting, nutrient depletion, and quality deterioration.

2.2 Mechanical Damage

Bruising, cuts, abrasions, and compression may occur during harvesting, grading, packaging, loading, transportation, and unloading. Mechanical injuries damage tissues and create entry points for microorganisms, thereby increasing the risk of decay.

2.3 Microbial Decay

Fungi and bacteria are major causes of post-harvest deterioration. Microbial infections are particularly likely when produce has mechanical wounds or is exposed to unsuitable temperature and humidity conditions.

2.4 Environmental Stress

Improper temperature, relative humidity, ventilation, and exposure to unsuitable atmospheric conditions can accelerate physiological deterioration. Temperature management is particularly important because lower temperatures generally slow respiration and microbial development, although chilling-sensitive vegetables can be damaged by excessive cooling.

2.5 Systemic Constraints

Inadequate cold-storage facilities, poor transportation infrastructure, limited access to appropriate packaging, insufficient farmer training, and inefficient marketing systems can increase post-harvest losses. Cold-chain development is therefore important for maintaining quality from farm to consumer (Bai *et al*., 2023).

3. Innovative Post-Harvest Technologies

3.1 Pre-Cooling

Pre-cooling is the rapid removal of field heat from freshly harvested produce before storage or transportation. It is one of the most important initial post-harvest operations because rapid cooling reduces respiration, water loss, and deterioration.

The main objectives of pre-cooling are to:

- Remove field heat.
- Reduce respiration and metabolic activity.
- Reduce moisture loss.
- Delay ripening and senescence.
- Reduce microbial growth.
- Maintain freshness and firmness.
- Extend post-harvest life.

The appropriate cooling temperature varies considerably among vegetable crops and should therefore be determined according to the specific commodity rather than applying one temperature to all vegetables.

3.2 Methods of Pre-Cooling

Vacuum Cooling

Vacuum cooling involves placing produce inside a sealed chamber and reducing atmospheric pressure. Water in the produce evaporates at a lower temperature, and the latent heat required for evaporation rapidly cools the commodity.

Advantages:

- Rapid and relatively uniform cooling.
- Particularly effective for leafy vegetables.
- Can rapidly remove field heat.

Disadvantages:

- High initial equipment cost.
- Some water loss occurs during cooling.
- Not suitable for all types of vegetables.

Hydro-Cooling

Hydro-cooling uses chilled water to remove heat from harvested vegetables. It can provide rapid cooling and, where appropriate, can simultaneously wash the produce.

Advantages:

- Rapid heat removal.
- Lower moisture loss compared with air cooling.
- Suitable for selected water-tolerant vegetables.

Disadvantages:

- Requires good water quality and sanitation.
- Produce and packaging must tolerate contact with water.
- Poorly managed water can facilitate microbial contamination.

Ice Cooling

Ice cooling uses crushed or flaked ice in direct contact with produce or within suitable packages. Melting ice removes heat while maintaining high relative humidity.

Advantages:

- Rapid cooling.
- Reduces moisture loss.
- Can be useful for selected vegetables such as broccoli.

Disadvantages:

- Ice adds weight and handling requirements.
- Direct contact with ice may damage sensitive commodities.
- Wet conditions can increase microbial risks if sanitation is inadequate.

Room Cooling

Room cooling is a relatively simple method in which harvested produce is placed inside a refrigerated room and cooled by circulating cold air.

Advantages:

- Simple operation.
- Relatively low additional equipment requirements.
- Produce can sometimes be cooled and stored in the same facility.

Disadvantages:

- Slower than forced-air, hydro-, or vacuum cooling.
- Requires considerable cold-room capacity.
- Not ideal when very rapid removal of field heat is required.

4. Cold-Chain Management

A cold chain consists of temperature-controlled handling, storage, transportation, and distribution from harvest to the final consumer. Maintaining an appropriate temperature throughout the supply chain slows respiration, reduces microbial growth, limits water loss, and helps maintain freshness.Cold-chain systems can substantially reduce losses during storage and distribution. Bai *et al*. (2023) reported that storage and distribution are important stages of food loss and emphasized the role of smart cold-chain technologies in improving food preservation and traceability.

Advantages

- Reduces post-harvest deterioration.
- Extends shelf life.
- Maintains colour, firmness, and freshness.
- Reduces microbial growth.
- Improves marketability.

Limitations

- High initial investment.
- Continuous energy requirements.
- Maintenance and operating costs.
- Requirement for trained personnel and reliable infrastructure.

5. Modified Atmosphere Packaging

Modified Atmosphere Packaging (MAP) involves modifying the gaseous environment surrounding fresh produce inside a package. The concentrations of oxygen (O_2), carbon dioxide (CO_2), and nitrogen (N_2) can be adjusted to reduce respiration and delay deterioration.

MAP can:

- Extend shelf life.
- Reduce respiration.
- Delay senescence.
- Reduce moisture loss.
- Help maintain colour and texture.

However, MAP must be designed according to the respiration rate and characteristics of the specific vegetable. Excessively low O_2 or excessively high CO_2 can result in anaerobic respiration, off-flavours, tissue injury, or other physiological disorders.

6. Controlled Atmosphere Storage

Controlled Atmosphere (CA) storage involves the continuous regulation of oxygen, carbon dioxide, temperature, and relative humidity. Unlike MAP, in which the atmosphere is modified within a package, CA storage generally involves controlling the atmosphere of the storage facility.

Advantages

- Slows respiration and metabolic activity.
- Delays senescence.
- Helps maintain firmness, colour, and quality.
- Can extend storage life under appropriate crop-specific conditions.

Limitations

- High installation cost.
- Requires continuous monitoring.
- Requires specialized equipment and trained operators.
- Incorrect atmospheric conditions may cause physiological disorders.

7. Nanotechnology in Post-Harvest Management

Nanotechnology involves the development and application of materials and systems at the nanoscale. In post-harvest management, nanotechnology is being investigated for applications such as nanocomposite packaging, nano-coatings, antimicrobial materials, and nanosensors.Nanoenabled packaging can potentially improve barrier properties against oxygen and moisture, while antimicrobial coatings may help suppress microbial growth. Nanosensors can also contribute to monitoring temperature, humidity, gases, and quality-related changes during storage.

Advantages

- Improved packaging barrier properties.
- Potential antimicrobial activity.
- Reduced oxygen and moisture transmission.
- Potential extension of shelf life.
- Development of smart packaging and monitoring systems.

Limitations

- High development and production costs for some nanomaterials.
- Requirement for advanced equipment and technical expertise.
- Need for careful assessment of safety, regulatory requirements, and environmental impacts before widespread food applications.

8. Comparison of Major Storage Technologies

Technology	Main principle	Typical application	Major advantage
Cold storage	Low temperature slows respiration and microbial growth	Potato, onion, cabbage, leafy vegetables	Extends storage life
Controlled atmosphere	Controls O_2 and CO_2 along with temperature and humidity	Selected vegetables	Delays senescence
Modified atmosphere packaging	Modifies gases around produce inside packaging	Broccoli, leafy vegetables, fresh-cut vegetables	Extends shelf life
Vacuum cooling	Evaporative cooling under reduced pressure	Lettuce, spinach, leafy vegetables	Very rapid cooling
Hydro-cooling	Chilled water removes field heat	Selected water-tolerant vegetables	Rapid cooling with low moisture loss

Technology	Main principle	Typical application	Major advantage
Ice cooling	Melting ice removes heat	Selected commodities such as broccoli	Rapid cooling and high humidity
Nanotechnology	Nano-coatings, nanocomposites, and nanosensors	Fresh vegetables and packaging	Antimicrobial protection and smart monitoring
Evaporative cooling	Evaporation lowers produce temperature	Smallholder/off-grid systems	Low-energy alternative

Passive evaporative cooling is particularly promising for smallholder farmers and areas without reliable electricity. Defraeye *et al*., (2023) found that its effectiveness depends strongly on local temperature and humidity. Under suitable conditions, evaporative cooling can reduce produce temperature and extend post-harvest life, making it a potentially useful low-cost technology in appropriate regions.

9. Future Prospects

Future post-harvest systems are likely to combine conventional technologies with digital and smart technologies. Important areas of development include sensor-integrated cold chains, solar-powered refrigeration, evaporative cooling systems for off-grid areas, crop-specific MAP, non-thermal treatments such as ozone and UV-C, cold plasma, and intelligent packaging.IoT-based sensors can provide continuous information about temperature, humidity, gas composition, and transportation conditions. Such real-time monitoring can help identify breaks in the cold chain and allow corrective action before significant quality deterioration occurs.Low-cost and energy-efficient technologies are particularly important for developing countries, where expensive refrigerated infrastructure may not be accessible to smallholder farmers. Passive evaporative cooling is one promising option because it can operate with relatively simple infrastructure and without conventional refrigeration, although its performance depends strongly on climatic conditions (Defraeye *et al*., 2023).

10. Conclusion

Post-harvest losses remain a major challenge in vegetable production because vegetables are highly perishable and continue to undergo physiological and biochemical changes after harvest. Appropriate post-harvest management can significantly reduce deterioration and preserve quality.

Pre-cooling, cold-chain management, MAP, CA storage, evaporative cooling, and nanotechnology-based packaging and monitoring **systems** offer different approaches to controlling temperature, humidity, respiration, microbial growth, and atmospheric composition.No single technology is suitable for every vegetable. Therefore, future post-harvest systems should emphasize crop-specific technologies and integration of multiple approaches from harvesting through transportation, storage, and marketing. Combining appropriate cooling with improved packaging, sanitation, monitoring, and infrastructure can contribute to lower food losses, better farmer income, improved food security, and a more sustainable vegetable supply chain.

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