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ADVANCES AND INNOVATIONS IN AGRICULTURE AND ALLIED SCIENCES

Editors:
Prof. (Dr.) Sanjay Khajuria
Dr. Mumtaz Baig
Ms. Vaishnavi Ghadage
Dr. Brijesh Kumar

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Advances and Innovations in Agriculture and Allied Sciences

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Editors

Prof. (Dr.) Sanjay Khajuria

Chief Scientist & Head

Krishi Vigyan Kendra Samba,

SKUAST Jammu, UT of J& K

Dr. Mumtaz Baig

Head, Department of Botany,

Dr. Rafiq Zakaria College for Women,

Aurangabad, M.S.

Ms. Vaishnavi Ghadage

Department of Zoology, M.M. College of Arts,

N.M. Institute of Science & H.R.J. College of

Commerce, Bhavan's College (Autonomous),

Andheri West, Mumbai

Dr. Brijesh Kumar

Department of Soil Science,

Dr. Rajendra Prasad Central Agricultural

University, Pusa (Samastipur),

Bihar

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Nigave Khalasa, Tal – Karveer, Dist – Kolhapur, Maharashtra, INDIA 416 207

E-mail: bhumipublishing@gmail.com

PREFACE

The book *"Advances and Innovations in Agriculture and Allied Sciences"* is a comprehensive compilation that highlights the latest developments, research trends, and technological breakthroughs shaping modern agriculture and its allied sectors. Agriculture, being the cornerstone of human civilization and economic stability, has undergone significant transformation over recent decades due to advancements in biotechnology, precision farming, sustainable resource management, and digital innovations. This volume seeks to present a broad spectrum of studies and perspectives that address contemporary challenges while showcasing novel strategies for enhancing productivity, sustainability, and resilience in the agricultural ecosystem.

The chapters included in this book cover a wide range of topics, including crop improvement, soil health management, water conservation techniques, animal husbandry, aquaculture, food processing, and agri-entrepreneurship. The contributors—researchers, academicians, and professionals—have provided valuable insights into integrating science and technology for sustainable agricultural development. Special emphasis is given to environmentally friendly practices, climate-smart approaches, and innovations that empower farmers and rural communities.

The book aims to serve as a useful reference for students, researchers, educators, policymakers, and practitioners working in agriculture and allied sciences. It not only bridges the gap between traditional practices and modern technologies but also encourages interdisciplinary collaboration to meet the global demand for food security and sustainable livelihoods.

We extend our sincere gratitude to all contributors for their scholarly efforts and commitment, and to the publishers for their continuous support in bringing this work to fruition. It is our hope that this volume will inspire further research, innovation, and knowledge sharing to promote a sustainable and prosperous agricultural future for generations to come.

- Editors

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GENOME-WIDE SELECTION:
THE ESSENCE OF CLIMATE RESILIENCE IN MAIZE

Yashaswini R*[1], P H Kuchanur[1], Prem Sagar S P[1], Raghavendra V C[1] and Sridhara M R[2]

[1]Department of Genetics and Plant Breeding,
University of Agricultural Sciences, Raichur - 584104 (Karnataka), India
[2]Department of Agronomy,
University of Agricultural Sciences, Raichur - 584104 (Karnataka), India
*Corresponding author E-mail: yashaswinirayanki1998@gmail.com

Abstract:

The chapter reviews the transformative role of genome-wide selection (GS) in improving maize for climate resilience. It highlights GS as a predictive breeding approach leveraging genome-wide marker data to estimate genomic estimated breeding values (GEBVs), enabling accelerated selection for complex traits such as drought and heat tolerance that are crucial under climate change. The chapter integrates recent empirical studies demonstrating rapid cycling genomic selection (RCGS) in multi-parental and landrace-derived maize populations, which achieve significant genetic gains and maintain diversity while reducing breeding cycle time. It discusses critical factors influencing GS accuracy, including training population design, marker density, trait heritability and statistical prediction models. The chapter outlines the advantages of GS over traditional marker-assisted selection (MAS), particularly for polygenic traits and emphasizes the necessity for continuous model retraining and integration with multi-environment data. Ultimately, the chapter positions GS as a pivotal strategy to enhance genetic gain, sustainability and food security in maize breeding against escalating climate stresses.

Keywords: Climate Resilience, Genomics, Heat and Drought Stress, Maize Breeding

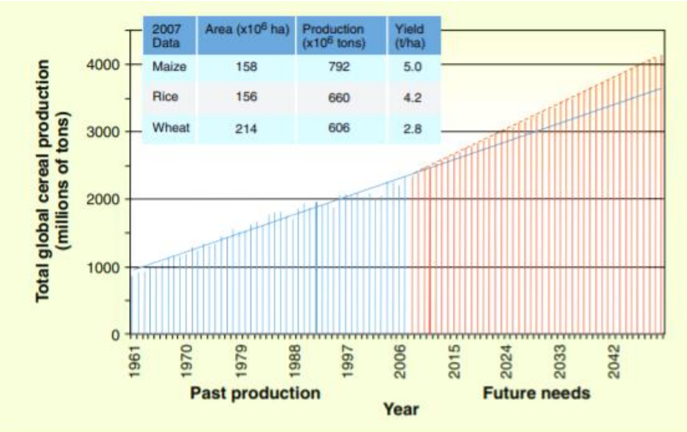
Introduction:

Maize is the third most important staple cereal crop across the globe, has been threatened with different environmental constraints including heat and water deficit stress. Drought with higher environmental temperatures negatively affect the most at anthesis, silking and grain filling reproductive phenophases, as a result there is reduction in grain yield by 58 per cent under drought and 77 per cent under combined drought and heat stress. Climate Resilient Crops and crop varieties have been recommended as a way for farmers to cope with or adapt to this climate change. Climate resilience can be generally defined as the adaptive capacity for a socio-ecological system to absorb stresses and maintain function and also to adapt, reorganize and evolve into more desirable configurations that improve the sustainability of the ecosystem leaving it to better prepared for the future climate change impacts (Meseka *et al.,* 2018).

As the marker assisted selection (MAS) is not efficient in capturing all the favorable alleles responsible for economic traits in the process of crop improvement. Genomic selection (GS) developed in livestock breeding and then adapted to plant breeding promised to overcome the drawbacks of MAS and significantly improve complicated traits controlled by gene/QTL with small effects, which acts as the major essence of the climate resilience in maize breeding (Meuwissen *et al.,* 2001). Genome-wide selection or GS hypothesizes that at least one marker from among the high density of genome wide markers is considered to be associated with a locus related to the target trait and quantifies the effect of that locus by adding to the estimated breeding value of an individual called the genomic estimated breeding value (GEBV).

Cereal crops play a crucial role in fulfilling the world's food, feed and nutritional needs; however, their long-term production growth may be seriously threatened by changing climatic conditions.

This below picture depicts the target of cereal production. Global cereal production has risen from 877 mmt in 1961 to 2351 mmt in 2007. However, to meet predicted demands production will need to rise to over 4000 mmt by 2050. However, with the world population projected to reach 9 billion by 2050, it is very essential to increase cereal production by 37% annually.



Although, there is huge potential to increase production of cereals through area expansion in some countries (SSA), uncontrolled area expansion cannot be a solution for meeting increasing demands, as this could potentially threaten forests, marginal lands, and hill slopes. Therefore, the genetic improvement of crop cultivars through plant breeding is likely to play a crucial role for global food security (Beyene *et al.*, 2016).

Current scenario of maize (FAOSTAT 2023-24; INDIASTAT 2023-24)

	Area (million ha)	**Production (m tonnes)**	**Productivity (kg ha^{-1})**
World	203.50	1163.70	5718
India	11.24	37.66	3351
Karnataka	1.97	5.62	2855

Maize is amongst the world's most widely produced and consumed cereal crops. Because of its high genetic yield potential, it called as Queen of cereals. The contribution of maize to food security is immense, and it is a staple food for more than 900 million poor people. About, 120-140 million farm families, depend on this crop for their livelihoods.

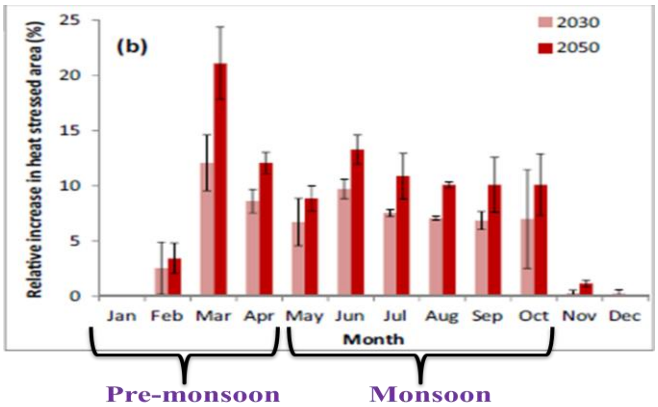
Globally, in 2019, about 1150 mmt of maize was produced covering an area of about 197 mha across 170 countries. During this year, global consumption of top three cereals (maize, wheat and rice) stood at 2365 mmt of which maize held about 48% share. India ranks 4th in terms of area and 7th interms of production of maize. Over the last few decades, maize cultivation has shifted from being grown only during *kharif* season in traditional areas (Such as Rajasthan, UP, Bihar) primarily to be used as food, to being grown across non-traditional areas (AP, MP, KA) across seasons, mainly for industrial purpose. However, the production system continues to be largely rainfed grown by small and marginal farmer. Among the total production of 28.08 mmt 14% share held by Karnataka.

Agricultural system extremely vulnerable to climate change

As we all know that agriculture system is extremely vulnerable to climate change. According t the report of Intergovernmental Panel on Climate Change, global mean temperature will raise 0.3˚C per decade reaching to approximately 1˚C and 3˚C above the present value by the year 2025 and 2100, respectively and which will result in global warming. Due to erratic distribution of rainfall and rising in temperature simultaneous occurrence of drought and heat stresses in farmer's fields are becoming increasingly common in tropical land, particularly in maize growing areas. If these current trends persist by 2050, maize yields may drop by 17%, wheat by 12% and rice by 10% because of climate change induced heat and water stress. It will be resulting in food scarcity will lead to higher prices and reduced caloric intake across regions (Meseka *et al.,* 2018).

Drought and heat stresses

Climate change poses a great threat to the sustainable development of South Asia (SA). Warming has occurred across most of SA over the centuries with more frequent incidences of temperature extremes.



Increase in heat stressed area (%) in South Asia (Kindie *et al.,* 2017). The heat stress affected area in SA will increase under the future climate, particularly in the pre-monsoon and monsoon season. Relative to the baseline, the increase in heat-stressed areas ranged from 3% (February) to 12% (March) in 2030 and 3% (February) t 21% (March) in 2050. While March to October will be the period for future increase in heat stressed areas.

Genome-wide Selection (GS)

Advances in genomic technologies have systematically transformed plant breeding from art to productive science. Recent developments in plant breeding and improved crop management practices have significantly contributed to improving the productivity of major crops. With the demand for food and nutritional security created by the growing population, a further increase in the yield potential of food crops along with nutritional quality is imperative. Considering the significant change in the climate, it is necessary to develop crop varieties that cope with the changing climate without compromising yield. Post-green revolution, yield levels in several major crops have reached a plateau and the growth rate of yield has slowed down. Genetic gain of at least 2.4 per cent is required to meet the 2050.

Parallel to this, increased anthropological activities have shrinked the available productive land for cultivation, hence, reinforcing the need to increase productivity of crops from available arable lands. Therefore, improving genetic gain is the only crucial way to reduce the gap between demand and food production. These demands pressurize researchers to improve existing cultivars and also develop new cultivars that can produce higher yield with more nutrition and plasticity to withstand climatic vagaries. Conventional plant breeding methods have significantly contributed to enhancing productivity. However, it is difficult to depend on conventional methods to meet future targets. Earlier, researchers selected breeding lines based on their phenotype, including yield attributing, for developing high-yielding varieties. However, many of these yields and yield-related traits are complex and controlled by several QTL with minor effects, significantly affected by the environment. Hence, improving these traits only by phenotype-based selection is not effective. In this scenario, there is a strong need to find new ways of improving genetic gains and improving productivity. Since 2000, there was a significant advancement in plant breeding methods, molecular biology, genomic technology, biotechnology, and data science, which has opened new avenues to address many complex issues related to crop improvement. Breeders need to be smart in their selection and development of cultivars by adopting the available plethora of new technologies in their regular breeding programs.

The application of DNA markers changed the perspective of crop improvement by acting as surrogates to select many complex phenotype traits that led to marker assisted selection (MAS). The principle of MAS has been extended to defect correction of elite cultivars via marker assisted backcross breeding programmes (MABB) and population improvement by accumulating relatively positive alleles for a trait via marker assisted recurrent selection (MARS) programs. Major known QTL were used as building blocks to design desired genotypes by introgressing them to agronomically superior recipient genotypes. For example, introgression of QTL associated with submergence tolerance (sub1), salt tolerance (saltol), drought tolerance (qDTY), BLB resistance (xa5, xa13 and Xa21) and BPH tolerance (QBph3, QBph4 and QBph35) are successful in many public and private sector paddy varieties and hybrids.

Likewise, other breeding by design approaches such as crossing elite parents that carry genes or QTL alleles, or by F_2 enrichment (inter-se crossing of QTL containing plants) followed by selection of desired plants have been implemented. However, MAS was only partially successful in selecting complex traits controlled by QTL with relatively larger effects, and it has not been effective in selecting traits controlled by a large number of QTL with none exerting large or consistent effects. Discovering and validating such a large number of low-effect QTLs are rather difficult. Even if such QTL are discovered and validated, pyramiding them in a genetic background that is agronomically superior is difficult. Furthermore, most economically important traits such as yield are complex and controlled by several small-effect genes/QTL, having a significant influence of the environment on their expression. This genes/QTL all together can produce a significant effect, but individual effects are too small to capture.

A predictive rather than a design approach is likely to be effective for genetic improvement of traits controlled by a large number of small-effective QTLs. In the predictive approach, DNA markers are not used as building blocks to design a desired genotype that is subsequently used as a cultivar (if found superior to the existing check cultivar) for commercial crop production. Instead, a large number of random markers are used as tools to predict the best genotype that exists in a population developed for cultivar development, and selection is conducted on the basis of predicted values. This alternate breeding procedure with a wholistic approach to capture the effects of all major and minor alleles/genes influencing complex traits is proposed as genomic selection (GS). GS hypothesizes that at least one marker from among the high density of genome wide markers considered is associated with a locus related to the target trait and quantifies the effect of that locus by adding to the estimated breeding value of an individual called the genomic estimated breeding value (GEBV).

In addition, it denies the necessity of identifying and mapping QTL for target traits and also phenotyping in later stages of breeding. Thus, while conventional MAS involves designing a desired genotype by introgression (by backcrossing) of or F_2 enrichment of QTL declared statistically significant, GS involves selection of best genotypes predicted based on a large number of statistically un-tested random marker effects. Therefore, GS could be described as MAS without QTL mapping. Apart from that, GS helps to reduce the duration of the breeding programme by reducing the number of breeding cycles required to achieve the target. Though efforts have been made by researchers to optimize GS models, less research has been made towards integrating GS with other disciplines. This review highlights the importance of an appropriate optimized GS model, the global open-source network for GS, and trans-disciplinary approaches for effective accelerated crop improvement.

Genetic gain: A measure of genetic progress in the breeding programmes

The genetic improvement or response to selection in breeding programmes is generally evaluated by the genetic gains obtained annually or per unit time *i.e.,* the quantity of increase in the performance of a breeding population/line obtained by selections in a year or unit time.

The expected value of genetic gains is estimated using the popular breeder's equation:

$$\Delta G = ih\sigma_a / L$$

Where,

i is the selection intensity,

h is the narrow sense heritability, σ_a is the additive genetic variance,

L is the length of breeding cycle interval or generation.

The breeding or selection approaches that allow rapid changes in the factors contributing to genetic gain *i.e*., methods which allow rapid increase in selection intensity, genetic diversity in the breeding population and/or heritability of traits and reduction in the length of the breeding cycles are needed to obtain higher genetic gains in breeding programmes.

GS and its advantages over traditional methods and MAS

GS was proposed for the first time in 2001 by Meuwissen *et al* in dairy cattle breeding. Since then, GS has been successfully applied in many cattle breeding programmes, and the genetic gains attained per generation with GS have doubled compared to traditional breeding methods in cattle. Over the years, the application of GS in crop plants and tree species has also been recognized owing to its great potential for enhanced/ speeded breeding. Basically, GS is a form of MAS with extended scope and advantages. GS involves estimation of effects of several genome wide markers, at the same time, to compute the genetic values, i.e., genomic estimated breeding value (GEBV) of the untested populations instead of only a subset of markers used for selection as in case of MAS.

In MAS, prior identification and mapping of genes or QTLs related to the traits of interest, estimations of marker-trait associations and their validation in different populations is required. Further, it explains only a limited part of the genetic variations for a trait, *i.e*., QTLs with small effects would not be detected. In contrast, GS eliminates the need for mapping of genes/QTLs associated with traits and instead follows a black-box approach involving the use of genome wide markers and is capable of identifying all the QTLs, including those with small effects that are missed by MAS. As per the principle of GS, genome wide markers are used to capture all possible genetic variations in the population and each QTL governing a trait is in linkage disequilibrium (LD) with at least one marker. The accuracy of GS relies on LD between specific alleles of markers and QTL, the stronger the LD between the two, the greater is the accuracy of genomic predictions. Further, as GS does not follow a "breeding by design" approach for crop improvement (as followed in MAS and conventional breeding) that requires previous knowledge of genes/QTLs governing traits for breeding, hence use of GS in breeding programs can overcome the huge costs and time involved in the process. GS also facilitates rapid selection of genotypes with superior performance and accelerates the breeding cycle by increasing the intensity and accuracy of selections thereby providing a reliable selection needed for faster genetic progress in breeding for complex traits.

Over the years, the advantages of GS over traditional breeding methodologies have been demonstrated in different crops. GS with a prediction accuracy of 0.53 resulted in multifold annual genetic gains compared to MAS and pedigree selection (PS) in maize and wheat. In maize, the average gain in grain yield was approximately up to 20% in GS compared to PS in eight bi-parental populations under drought stress. In common buckwheat (*Fagopyrum esculentum*), an allogamous pseudo grain crop, the mean selection index was enhanced by about 21% from the initial population in GS as compared to 15% in PS breeding over three years. In soft red winter wheat, the gain in response for grain yield and agronomic traits was 10% when the phenotypic selection was supplemented with GS as compared to using PS alone.

Further, recent advances in statistics, cost- effective high-throughput SNP chips and next-generation sequencing (NGS) platforms have enabled genotyping of large breeding populations at much-reduced costs than earlier. However, the increase in the cost of resources such as land, labour, water, and other crop inputs is becoming a limiting factor for large scale multi-environment field testing of breeding lines. Thus, GS not only allows an increase in the selection gains per unit time and cost for the complex traits with low heritability but is also ecofriendly as it reduces the use of crop inputs compared to MAS and PS.

A generalized procedure for genome-wide selection

The GS method is based on two separates, but related, populations, *viz*., a training population and a breeding population. The training population is used for training of the GS model and for obtaining estimates of the marker-associated effects needed for estimation of GEBVs of individuals/lines in the breeding population. The breeding population, on the other hand, is the population subjected to GS for achieving the desired improvement and isolation of superior lines for use as new varieties/parents of new improved hybrids.

1. The first step in a GS program is to create a training population suitable for the concerned breeding population.
2. The individuals/lines in the training population are genotyped for a large number of markers evenly distributed over the entire genome at adequate density.
3. The individuals/lines in the training population are subjected to extensive phenotypic evaluation for the target trait(s) in replicated trials over locations and, preferably, years.
4. The phenotype and marker genotype data are used for computing the GS model parameters; this is called model training. Model training can be performed repeatedly to include data on

new markers and additional traits. The estimates of GS model parameters are retained for subsequent application to the breeding population.

5. The breeding population is evaluated for the same set of markers that was used for estimation of the model parameters in the training population. There is no phenotypic evaluation of the breeding population.
6. The GEBVs of individuals/lines of the breeding population are calculated from their marker genotype data and the marker- associated effects estimated from the training population.
7. The superior individuals/lines are selected from the breeding population on the basis of their GEBV estimates.

Genome-wide Selection methodology

The fundamental process of GS involves estimation of the breeding values for the lines under testing only based on the genotypic data using statistical models developed in a reference/training population (TP). A TP consists of the population having comprehensive phenotypic and genotypic data and using which GS model parameters are derived. Subsequently, the GS models are used to estimate breeding values referred to as genomic estimated breeding value (GEBV) of the lines of the breeding population (BP) based on the genotypic data. TP is a set of related individuals whose descendancy is known, like half-sibs or closely related populations. BP is comprised of the descendants of TP or elite lines that are closely related to the TP. Genetic values of a BP for different traits are predicted using allelic similarity with loci which are associated with the phenotype in the TP. Therefore, GS depends on the degree of genetic similarity between TP and BP in the linkage disequilibrium (LD) between marker and trait loci. GEBV is obtained on the combination of genome wide desirable loci of the BP and further, it provides an estimation of superior phenotype through high breeding values without testing them phenotypically under field conditions (Voss- fels *et al.*, 2019). Lines in the BP, which possess high GEBV, are further selected as new breeding parents to pyramid desirable alleles for the subsequent cycle of selection or subjected to multi- environment evaluations for release as an elite/new variety. A schematic representation of GS in crop plants is presented below.

Training population

The training population must be representative of the breeding population. It should maximize the proportion of trait variance associated with the markers. This can be achieved by including in the population such individuals/lines that have divergent GEBVs. The training population should exhibit low collinearity between markers. Colinearity between markers is disturbed by recombination; therefore, the individuals/lines included in the training population should have undergone several rounds of recombination. Low colinearity between markers is needed since high colinearity tends to reduce prediction accuracy of certain GS models. Finally, the training population should adequately represent the genetic diversity present in the breeding population. This could be achieved by selecting individual/ lines from the breeding population on the basis of some form of cluster analysis and including them in the training population.

Design of training population (TP)

The design of TP plays a pivotal role in the success of GS by contributing to high prediction accuracy in BP, thereby enabling the selection of true candidates in active breeding programs. TP composition could be individuals selected within a single bi-parental family or accessions of germplasm collection. The key consideration of TP design is the BP composition, therefore, BP needs to be defined first followed by the TP design that revolves around the aims of minimizing costs associated with phenotyping/genotyping and maximizing the prediction accuracy of the candidates. However, different TP designs are possible under different breeding scenarios such as (Anilkumar *et al.*, 2022).

1. Training and breeding population lines are segregating progenies from the same cross

Individuals from the same family or biparental crossing are used as both the TP and BP. All the individuals of a cross are genotyped and only a subset of these individuals are phenotyped to serve as the TP needed for training a genomic prediction model and then the model is used to predict the genetic value of individuals (BP) that are left without phenotyping. Further, the trained model can also be used to predict future selection cycles in the populations generated by intermating of the selected individuals of the family. This TP design has been extensively studied in different breeding programmes with large bi-parental families or doubled haploids. A large number of studies have been carried out in wheat, maize, rice, and rye. The advantage of the within family based genomic predictions is that a good prediction accuracy can be achieved with a relatively fewer number of markers and population size. Here, better accuracy is possible due to the high LD present in segregating populations of an initial hybridization cycle, which is similar to the power of QTL mapping in biparental populations. The disadvantages of this TP design are the high costs involved in genotyping of large individuals in segregating generations and phenotypic data from replicated and multilocation trials of the individuals and moreover, the non-fixation of alleles in the populations may affect the training of an efficient GS model.

2. Training and breeding population lines comprising of both related and unrelated genotypes

Practically, prediction models developed from single biparental populations have limited applications outside of particular breeding systems. Therefore, TP designs that combine data from both related and unrelated families would be more useful for plant breeders. TP needs to be created by pooling together progenies of different pedigrees and genetic backgrounds with various levels of relatedness, including full sibs, half-sibs and other individuals with related ancestry. Numerous studies have demonstrated that the prediction accuracy of GS substantially reduces when TPs are not related to the breeding lines. In hybrid wheat, the prediction accuracy for genomic prediction for disease resistance was much higher for related sets ranging between 0.65-0.92 as compared to 0.06-0.43 in unrelated with prediction accuracies of 0.4-0.55 for half-sibs and 0.28-0.42 for unrelated individuals. Studied maize data sets for grain dry matter yield and content. It was observed prediction accuracies ranging from 0.72-0.74 for related individuals as compared to lower accuracies with 0.47-0.48 for unrelated individuals. Results also suggest that combining large number of families to predict a particular target family has generally indicated that better prediction accuracies are obtained when the pooled families share one of the parents with the breeding/target population. The inclusion of families sharing one parent with the family-specific TP could help in increasing the prediction accuracy compared to the family-specific TP alone, particularly for small target family size. Similarly, Shikha *et al.,* 2017 studied the usefulness of multiparental maize populations for genomic selection, and found that comparable predictive abilities within biparental families could be achieved by adding several half-sib families in the estimation set. Prediction accuracy with 375 half-sib lines of maize was similar to that was obtained with 50 full-sib lines for predicting the biomass yield. Further, it is suggested that the use of high-density markers may improve the prediction accuracy of unrelated families by sharing the marker information between families. The main advantage of this TP design is that it suits well to implement GS in ongoing breeding programmes, as this design includes both closely related as well as less closely related individuals. Generally, TPs consisting of only unrelated individuals to the BP result in very low to zero prediction accuracy.

3. Training and breeding lines comprising of lines from a diverse germplasm collection

Apart from predicting the breeding value of progenies from an active breeding program, another role of GS includes the prediction of diverse germplasm collection. Gene banks contain huge collections of accessions and identifying a few desirable accessions is a challenging task through phenotyping of entire gene bank collections. High-throughput genotyping platforms have made it possible to genotype a large number of germplasm collections that could enable the prediction of performance of the germplasm accessions. The usefulness of GS in tapping the germplasm potential is demonstrated in various crop plants including wheat, sorghum, soybean, lentil, and sugarbeet.

It has been found that GS can be efficiently used to unlock the potential of larger germplasm collections even with the lower-density genotyping methods and through well representation of the selection population in TP. In spring wheat, the potential application of GS for utilization of germplasm accessions, a total of 1163 germplasm were phenotyped for adult plant resistance to stripe rust (*Puccinia striiformis* f. sp. *tritici*) and genotyped using a 9K SNP array and various genomic prediction schemes were analysed. The results showed that prediction accuracy improved with an increase in TP size and density of markers. Prediction accuracies increased from 0.50 to 0.63 when the TP size was increased from 210 to 959 at an average of 1% increase for every 50 individuals increase in the TP size. It was observed that no further increase in prediction accuracy was observed beyond an SNP marker density of 1 per 3.2 cM. Further increase in prediction accuracy was observed in the subpopulations formed based on within the kinship and structure analysis. In a subpopulation, it ranged up to 0.75 to 0.79 whereas in another it was 0.51 to 0.58. The degree of prediction accuracies in the two subpopulations was correlated with the degree of genetic relatedness among accessions in each subpopulation indicating that genetic relationships between the TP and selection population are critical for making selections from germplasm collections. This TP design is advantageous in the identification of potential germplasm accessions having high GEBVs out of entire germplasm accessions through GS. This is one of the possible complementary strategies to exploit the valuable gene bank accessions, as phenotyping of entire collection is a challenging task due to various practical difficulties.

Breeding population

The breeding population consists of descendants of the training population or individuals that are closely related to the training population. Breeding values of individuals in a breeding population are predicted based on allelic similarity associated with trait phenotype in the training population. Lines (F_2, F_3…, DH or RIL) derived from natural or designed populations could be used as a breeding population. Balanced relationship between TP and BP The closer relationship between TP and BP ensures higher prediction accuracy in genomic selection. Several researchers demonstrated improved prediction accuracy using related TP and BP. Composing BP using full sibs showed higher accuracy than using half-sib families owing to higher relatedness in full-sibs. Increasing relatedness by including more closely related crosses in TP is more important than increasing the size of TP with unrelated crosses. For a highly heritable trait, showed 50 full-sibs were sufficient to achieve predictive power of 375–675 half-sibs. Population structure and/or diversity in the training population may affect the composition of the training and breeding populations, thereby affecting prediction accuracy. When TP and BP were composed of segregating lines from the same cross, the genomic selection model accuracy was found to be higher than any other TP structure.

In cross-validation sets, stratified sampling ensures a representative from each of the sub-populations in each of the cross-validation folds outperforms random sampling. Similar findings were reported by, where high accuracy was achieved when progeny prediction was based on a model trained on TP with related individuals/parents. Optimization of size considering the genetic structure and relationship between TP and BP is more successful. With the inclusion of the environmental component for prediction, sampling or choice of TP individuals with low GEI improved prediction accuracy. Designing TP by including individuals both from related and unrelated groups would be more beneficial to breeders. Pooling the progenies from different families sharing nearly the same ancestry with different levels of relatedness will extend the power of TP to employ genomic selection in varied sets of populations. However, this approach is not common in genomic selection since the power of genomic selection will be substantially reduced when TP is not closely related to BP.

Balanced relationship between TP and BP

The closer relationship between TP and BP ensures higher prediction accuracy in genomic selection. Several researchers demonstrated improved prediction accuracy using related TP and BP. Composing BP using full sibs showed higher accuracy than using half-sib families owing to higher relatedness in full-sibs. Increasing relatedness by including more closely related crosses in TP is more important than increasing the size of TP with unrelated crosses. For a highly heritable trait, showed 50 full-sibs were sufficient to achieve predictive power of 375–675 half-sibs. Population structure and/or diversity in the training population may affect the composition of the training and breeding populations, thereby affecting prediction accuracy. When TP and BP were composed of segregating lines from the same cross, the genomic selection model accuracy was found to be higher than any other TP structure. In cross-validation sets, stratified sampling ensures a representative from each of the sub-populations in each of the cross-validation folds outperforms random sampling. Similar findings were reported by and where high accuracy was achieved when progeny prediction was based on a model trained on TP with related individuals/parents. Optimization of size considering the genetic structure and relationship between TP and BP is more successful. With the inclusion of the environmental component for prediction, sampling or choice of TP individuals with low GEI improved prediction accuracy. Designing TP by including individuals both from related and unrelated groups would be more beneficial to breeders. Pooling the progenies from different families sharing nearly the same ancestry with different levels of relatedness will extend the power of TP to employ genomic selection in varied sets of populations. However, this approach is not common in genomic selection since the power of genomic selection will be substantially reduced when TP is not closely related to BP.

Marker system

Genomic selection modelling assumes that some markers will always be in LD with any QTL/gene. It is convention to use uniformly distributed genome-wide markers for better results, but the marker density required (to achieve maximum genetic gain) to achieve accurate prediction needs to be optimized. Several reports suggest that increased accuracy of genomic prediction with an increase in marker density, however, reaches a plateau beyond optimum marker density. Marker density used for genomic prediction depends on the genetic structure of TP, LD status, relatedness between TP and BP, and trait heritability.

Marker type

A large number of markers, irrespective of whether SSR or SNP (the majority of GS studies used SNP), covering the whole genome are preferred. Despite SSR markers being more informative than SNPs, the availability and genome coverage of SSR markers is very poor compared to the SNP marker system. In the era of genome sequencing, use of the SNP marker system is more beneficial to cover the entire genome for genomic selection to be most effective. Apart from that, many of the statistical models developed for genomic selection are handier with SNP marker information. Marker density Prediction accuracy has been reported to increase with an increase in marker density only when trait heritability is high. Marker density is considered an extremely important factor influencing genomic selection accuracy. However, prediction accuracy was found to reach a plateau beyond higher marker densities and did not increase further. Since optimum marker density depends on the structure and level of LD in a population, it differs from population to population. Self-pollinated species and bi-parental crosses need less density of markers than natural populations owing to the population structure and high LD. Bi-parental populations will have limited recombination and ensure clear structure, which requires lower marker density than natural populations

Opined that marker density increases with an increase in Ne*c, where Ne is the effective population size and c is the recombination rate between loci. For instance, 1000 SNP markers were sufficient to achieve maximum prediction accuracy in maize using bi-parental populations. Biparental populations like RIL or DH with a narrow genetic base always have high LD between markers and QTL reported that the number of markers > 7500 (19 SNP per Mb) did not improve prediction accuracy among subsets of 73,147 SNPs on a population of 363 Indica rice lines. Similarly, concluded 13 SNPs and 27 SNPs per Mb in rice were sufficient to improve prediction accuracies, respectively. These disparities in optimal marker density reports could be attributed to differences in LD, reinforcing that lower marker density is associated with high LD (r^2 = 0.50). Studies have reported that prediction accuracy is affected by systematic selection or elimination of markers based on their effects.

Trait heritability

The prediction accuracy has a significant correlation with the heritability of traits, and it varies with the mode of pollination of crop species. Several studies have revealed that the accuracy of genomic selection increases with an increase in trait heritability reported poor predictive accuracy for those traits with poor heritability in a diverse panel consisting of 413 individuals of rice. Wheat flour quality traits, sucrose solvent retention, and protein content with heritability of 0.45 and 0.56, respectively, resulted in prediction accuracies of 0.74 and 0.64, respectively, indicating the importance of heritability of traits in improving prediction accuracies. On the contrary, considering the heritability of plant height (h^2 = 92.3%) and primary branches (h^2 = 78.7%), proved that there is no significant association between trait heritability and prediction accuracy. In the estimation of breeding values, use of narrow sense heritability is more appropriate than considering broad sense heritability in rice. While breeding for traits with low heritability, breeders should be more specific toward using high-density genotyping platforms or opt to pool multiple populations while designing training populations to increase the prediction accuracy of GEBVs. It is true that application of genomic selection could potentially improve the genetic gains even for traits with low heritability.

Appropriate statistical training models

To overcome the Beavis effect of biasness in MAS, Meuwissen *et al.* (2001) introduced genome-wide markers for estimating the marker effects associated with a complex trait. The equation, P = Σgixi + E is the basic model for genomic prediction, where gi is the effect associated with genotype at a marker locus and xi is the coded marker genotype. The performance of GS models should be tested trait-by-trait before adapting to a breeding program. The predictive models have been upgraded and replaced with preceding models depending on the requirements. Many investigators modified the genomic selection models to improve selection/prediction accuracy and integrate them with existing breeding methods. Their accuracy of prediction differs with differences in assumptions and marker effects considered. Even though several genomic selection models have been developed, choosing an appropriate model to realize maximum success is most critical. Among the available models, ridge regression best linear predictors (RR-BLUP) and genomic best linear unbiased prediction (G-BLUP) are the most used models in crop plants. The RR-BLUP model assumes that all the markers used have equal variances, whereas G-BLUP considers a genomic relationship matrix to estimate additive effects. However, fulfilling the assumption of equal variance of all markers in G-BLUP and RR-BLUP is unrealistic when most of the markers have negligible effects. Recently, a set of models called Bayesian models (including Bayes A, Bayes B, Bayes C, and LASSO) are more suitable for practical crop improvement situations. Each of these Bayesian models differs in their distribution and assumption of marker effects in realizing higher prediction accuracies.

Few researchers compared the effectiveness of models, compared nine GS models using a panel of 110 rice genotypes with eight agronomic characters and inferred that the G-BLUP and RR-BLUP models were the most accurate for one trait each, and the Reproducing Kernel Hilbert Space (RKHS) model for two traits. A similar kind of interpretation was also made with additional information on using random forest models for multiple traits to increase predictive ability. With the inclusion of G × E effects on trait expression, opined that the use of Gaussian kernel models provides much higher prediction accuracy than Bayesian models. The incorporation of data from emerging multi-omics technologies such as proteomics and metabolomics into the genomic selection model aided in the capture of non-additive effects and minor allelic effects. Developments in data science have supported the evolution of new models based on machine learning and deep learning tools in order to improve prediction accuracy and genetic gain in crop breeding.

Factors affecting prediction accuracy

Accuracy of prediction depends on the composition of the training population (size and genetic structure), markers (number), relationships between TP and BP, genetic architecture of the trait, and the model used. However, the precision of marker genotyping and its effects play an important role in the accuracy of genomic predictions, and methods used to improve marker effects are equally important. These factors are interconnected and are relative expressed the prediction accuracy as $rGM \approx ax1 + bx2 + cx3 + dx4 + ex5$, where x1, x2, x3, x5 are marker density, population size, relationship of training and breeding population, trait heritability, and genetic model effect, respectively, and a toe are constants associated with variables x1 to x5. There are several reports on the effect of each of these factors on prediction accuracy using cross-validation tests. However, the conclusions of these findings collectively help optimization of these factors to achieve higher prediction accuracy.

Cross - validation

In any successful genomic selection program, validating the accuracy of prediction estimates of models developed using a training population is crucial. The genetic variance estimated in most genomic selection models developed on training populations associated with trait-irrelevant markers leads to over-fitting of the model due to overestimation of trait heritability. Over-fitting of the genomic selection model can be controlled by performing a cross-validation experiment. Validation population is separately designated which is genotyped and phenotyped, GEBVs estimated for the validation population are compared with true breeding values of candidates in the validation set. To estimate the GEBVs in the validation population, the model developed for the training population is used along with the marker information from the validation set. The accuracy of predicted GEBVs is normally quantified as the correlation (r) between predicted GEBVs and true breeding values (g). However, direct computation of prediction accuracy for empirical data sets is not possible, because true breeding values are not known. Hence, correlation between predicted GEBVs and observed phenotype values (y), referred to as predictive ability (PA), and is often computed. In order to indirectly estimate GEBVs, prediction accuracy (PA) is divided by the square root of heritability (h) of the target trait.

The main purpose of cross-validation is to train appropriate best fit prediction model on training population to use further on breeding population for estimation of GEBVs (Perez- Cabal *et al.* 2012; Krishnappa *et al.* 2021). Among different approaches to cross-validation, ordinary least-square approaches are most common in genomic selection-assisted crop improvement. However, leave-one out cross-validation is one such ordinary least square based approach and is considered a special type of k-fold validation, used only when the population size is small and there is a limited size of training folds. If k-fold cross-validation is considered, the complete dataset is divided into k-groups and analysed 'k' times, where, out of k groups, one group is omitted from the training model and considered for validation in each analysis. In leave-one-out cross-validation, k = n, where n is population size, and this is considered only for experiments with low population size where the size of the training fold is limited. For example, the entire population of 200 individuals has been phenotyped and genotyped, and the individuals are randomly partitioned into 160 individuals as a training set (TS) and 40 individuals as a corresponding validation set (VS). The process of partitioning the training population into TS and VS is repeated many times to ensure a good estimate of the prediction accuracy. In the end, all the 200 individuals are analysed to obtain the final prediction equation. This is referred to as five-fold cross-validation.

	Subset 1	**Subset 2**	**Subset 3**	**Subset 4**	**Subset 5**
Fold 1	Training set	Training set	Training set	Training set	**Validation set**
Fold 2	Training set	Training set	Training set	**Validation set**	Training set
Fold 3	Training set	Training set	**Validation set**	Training set	Training set
Fold 4	Training set	**Validation set**	Training set	Training set	Training set
Fold 5	**Validation set**	Training set	Training set	Training set	Training set

On the other hand, leave-d-out is another approach where k is an arbitrary number; in this approach, d observations are omitted from the n observations available for model training and declared only for validation and testing the model. These least square-based approaches are limited to low population genomic selection experiments. While improvements in machine learning and deep learning tools introduced shrinkage in regression-based cross-validation for big data analytics in genomic selection, markers BLUP (ridge regression), RKHS regression, and GBLUP approaches are the most commonly used in crop improvement for model development and validation.

Genome-wide Selection *vs* Marker assisted selection

The general processes of GS and traditional MAS used for quantitative traits (QTs) are shown in Fig. 1. The main frameworks of the two approaches are similar, where both GS and traditional MAS consist of training and breeding phases. In the training phase, phenotypes and genome-wide (GW) genotypes are investigated in a subset of a population, i.e. the training population in GS and the mapping population in traditional MAS. Within populations, significant relationships between phenotypes and genotypes are predicted using statistical approaches. In the breeding phase, genotype data are obtained in a breeding population, before favourable individuals are selected based on the genotype data obtained. Three obvious differences between the two approaches are apparent: (1) in the training phase, quantitative trait loci (QTLs) are identified in traditional MAS while formulae for GEBV prediction are generated in GS, known as GS models; (2) in the breeding phase, genotype data are only required for targeted regions in traditional MAS, whereas GW genotype data are considered to be necessary in GS; (3) in the breeding phase, favorable individuals are selected based on the genotypes of markers in MAS, whereas GEBVs are used for selection in GS. Thus, GS jointly analyses all the genetic variance of each individual by summing the marker effects of GEBV, and it is expected to address small effect genes that cannot be captured by traditional MAS.

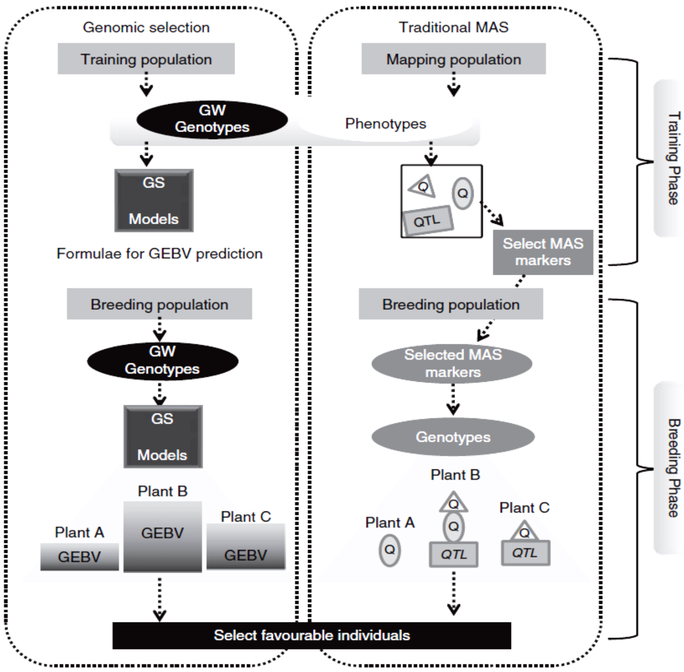
- **Bernardo and Yu (2007)** observed that genomic selection is superior over MARS for complex traits. Across different numbers of QTLs and levels of heritability, the response to GS was 18 to 43% larger than the response to MARS.
- **Ziyomo and Bernardo (2013)** showed that GS for drought resistance in maize has proven advantageous than the indirect phenotypic selection through secondary traits.
- **Beyene *et al.* (2014)** observed that hybrids derived from C_3 produced 7.3% higher GY than those developed through conventional pedigree breeding method.
- **Cerrudo *et al.* (2018)** observed that GS outperforms MAS for grain yield and physiological traits in a maize DH population across water treatments.

Strategic positioning of genome wide selection compared to other methodologies for gene discovery and selection for complex traits

The promise of genome-wide selection obviously does not imply that gene discovery should no longer be done. Several approaches for discovering QTL have been proposed: comparative genomics, association genetics, candidate-gene approach, and QTL mapping. These approaches for gene discovery will continue to be vital for increasing our basic knowledge of the genes underlying quantitative traits. Comparative genomics and association mapping usually focus on diverse germplasm, and the results from these approaches may not be readily applicable to selection in narrow, elite germplasm. Candidate gene approaches, which are not mutually exclusive of comparative genomics and association mapping, utilize biological knowledge to identify a few genes that may be introgressed into elite germplasm to improve quantitative trait.

Genome selection, in contrast, does not involve gene discovery. But even though MARS and genome wide selection do not emphasize gene discovery, QTL mapping can and should be done in conjunction with both MARS and genome wide selection. Although selection is genome wide, the markers with large, highly significant effects may be considered as putatively linked to major QTL.

Nakaya & Isobe — Genomic selection as a method for plant breeding



Rapid cycling genomic selection in a multi-parental tropical maize population

The article presents a pioneering study on rapid cycling genomic selection (RCGS) applied to a multi-parental tropical maize population composed of 18 elite CIMMYT lines. By conducting four cycles of genomic selection and recombination over 4.5 years, the study demonstrated realized genetic gains in grain yield of 0.225 tons per hectare per cycle, equivalent to 0.100 tons per hectare per year under optimal conditions. The approach effectively maintained genetic diversity up to the third cycle while achieving accelerated genetic gain, outperforming conventional pedigree selection timelines. The genomic prediction models incorporated dense genotyping-by-sequencing SNP data, enabling accurate selection and recombination in a multi-environment testing framework. This work establishes RCGS in multi-parental populations as an efficient strategy to enhance climate resilience in maize through rapid, data-driven improvement of yield under diverse tropical environments.

Rapid cycling genomic selection in maize landraces

The attached article reports a replicated rapid cycling genomic selection experiment conducted on a maize landrace population (Petkuser Ferdinand Rot) using doubled-haploid (DH) lines genotyped with a 600k SNP array. Three cycles of genomic selection and recombination were performed targeting early plant development traits critical for climate resilience, including early plant height at V4 and V6 growth stages and stabilizing final plant height. Genomic estimated breeding values (GEBVs) were calculated with multi-trait models, and selection response was evaluated through both genomic prediction and multi-environment field trials across European locations. Results showed significant selection gains for early plant height in the base cycle, with diminished but positive gains in successive cycles, accompanied by moderate decreases in genetic variance and prediction accuracy. Retraining prediction models with updated phenotypic data from selection cycles improved prediction accuracies, underscoring the need for periodic model updates in rapid cycling schemes. The study provides important experimental evidence that rapid recurrent genomic selection can effectively harness polygenic variation in heterogeneous landrace populations for pre-breeding climate-resilient maize germplasm, highlighting the balance between selection gains, diversity management, and retraining strategies.

Conclusion:

Climate change has accelerated the frequency and intensity of multiple abiotic and biotic stresses, including drought, heat, flooding and pest infestations, posing a serious threat to global food production. In field conditions, crops are often subjected to concurrent or sequential stress combinations that elicit unique physiological and molecular responses not predictable from individual stress analyses. Consequently, conventional breeding approaches targeting single-stress tolerance have limited success under such complex environmental interactions. In India, where agriculture sustains a major portion of the population, the development of climate-resilient crop varieties remains insufficient, highlighting the urgent need for advanced breeding methodologies capable of addressing multifactorial stress scenarios.

Genome-wide Selection represents a transformative approach for enhancing the rate of genetic gain and developing climate-resilient maize varieties. By employing genome-wide markers to predict breeding values, GS enables early and accurate selection, thereby reducing breeding cycle time and cost. Integration of GS with existing breeding programs enhances selection efficiency for complex quantitative traits associated with stress tolerance. Recent advancements in high-throughput genotyping and computational prediction models have further improved the precision and feasibility of GS. Continuous model optimization, validation, and incorporation of multi-environmental data are essential for its effective application. Strengthening GS-based breeding pipelines will be pivotal for accelerating genetic improvement in maize, ensuring sustainable productivity, and securing global food systems under the growing challenges of climate change.

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ICT, SMART FARMING AND DIGITAL AGRICULTURE

Avinash Mishra*[1], Manish Sharma[2],
Renu Singh[3], Kokab Ansari[4] and Twinkle Thapa[5]
[1]Sanskriti University, Mathura, U.P., India.
[2]Dr. Bhimrao Ambedkar University, U.P., India.
[3]KNIPSS, Sultanpur, U.P., India.
[4]Maharishi Markandeshwar Deemed to be University, Ambala, India.
[5]Sanskriti University, Mathura, U.P., India.
Corresponding author E-mail: avimishrapas@gmail.com

Abstract:

Information and communication technologies (ICT), digital agriculture, and smart farming are all combining to drive the 21st century agricultural revolution. Climate change, resource shortages, and rising food demand have rendered conventional methods insufficient, necessitating the use of technology-driven solutions. ICT makes it easier to share information, make decisions, access money, and connect with markets through tools like digital advisories, online platforms, and mobile applications. Big data analytics, blockchain, the Internet of Things (IoT), and precision farming are all integrated into digital agriculture to facilitate data-driven decision-making throughout the agricultural value chain. To increase productivity, sustainability, and climate resilience, smart farming, an advanced subset, makes use of robots, automation, artificial intelligence, and real-time monitoring. Examples such as e-Choupal, Digital Green, Israel's precision farming, and the Climate Corporation illustrate useful advantages like increased output, lower expenses, better market accessibility, and food traceability. Big adoption is still hampered by issues including the digital divide, low literacy, cost, and legislative inconsistencies. In order to overcome these limitations, policy measures, public-private partnerships, and farmer capacity-building are necessary. The potential for ICT and smart farming to transform smallholder agriculture is ultimately enormous, as it can guarantee food security, rural wealth, and sustainable development in the face of global concerns.

Introduction:

The 21st century has brought agriculture to a turning point. Global food demand has dramatically expanded due to factors like population expansion, fast urbanization, and shifting dietary habits. At the same time, agriculture has to contend with issues including decreasing arable land, deteriorating soil fertility, water scarcity, and climate change. Despite their effectiveness in the past, traditional farming methods are not enough to handle these new problems.

This is where smart farming, digital agriculture, and information and communication technologies (ICT) are useful. Through the utilization of contemporary digital technologies, including smartphones, drones, satellites, sensors, artificial intelligence (AI), and big data, farmers may obtain timely information, maximize input utilization, boost yields, cut expenses, and directly connect markets.

As a result, ICT in agriculture promotes inclusivity, sustainability, and resilience in addition to productivity.

The concept and relevance of ICT in agriculture

ICT includes technologies that make it easier to share knowledge, process information, and communicate. Given how information-intensive farming is, its function in agriculture is crucial. Regarding weather, soil health, pests, markets, and government programs, farmers require quick and accurate information.

ICT's primary functions in agriculture

1. Information sharing: Farmers can plan irrigation and seeding with the aid of weather forecasts:

- Alerts for pests and diseases lower crop losses.
- Government advisories are sent to farmers more quickly through mobile apps or SMS.

2. Assistance in making decisions:

- ICT provides farmers with decision support systems (e.g., which crop to sow, which variety to use, when to irrigate).
- Models use data on rainfall, soil, and crop stages to give precise recommendations.

3. Connections to the market:

By enabling farmers to sell directly to consumers throughout India, digital platforms such as e-NAM (Electronic National Agriculture Market) enhance price realization.

4. Access to finances:

- Online credit applications, crop insurance claims, and digital payments are all supported by ICT.
- Without the need for middlemen, mobile banking enables rural farmers to obtain loans and subsidies.

Example: In India, the *m-Kisan* portal delivers personalized SMS advisories to farmers in multiple regional languages, reaching millions of smallholders.

Digital Agriculture

Digital agriculture goes beyond communication—it involves the integration of data and technology into every step of the agricultural value chain.

Key Components of Digital Agriculture

1. **Precision Farming**:
   - Uses GPS, GIS, and sensors to apply water, fertilizers, and pesticides only where needed.
   - Reduces waste and increases efficiency.
2. **Big Data Analytics**:
   - Large datasets (on soil health, climate, yields, and markets) are analyzed to identify trends and support planning.
   - Helps in yield forecasting and supply chain optimization.
3. **Internet of Things (IoT)**:
   - Smart devices like soil sensors, automated irrigation systems, and weather stations provide real-time farm data.
4. **Blockchain Technology**:
   - Enhances traceability in food supply chains, ensuring quality assurance.
   - Consumers can track products from "farm to fork."
5. **Mobile Applications**:
   - Mobile apps provide extension services, price updates, and access to government schemes.
   - Examples: *Agri-App, Kisan Suvidha, IFFCO Kisan*.

Digital agriculture is data-driven farming, focusing on knowledge-based decisions rather than intuition.

4. Smart Farming: Concept and Technologies

Smart farming is a subset of digital agriculture where technology is integrated into farming operations for real-time monitoring, automation, and control.

Key Technologies in Smart Farming

- **Remote Sensing & GIS**: Satellites and drones capture high-resolution images for monitoring crop health, soil moisture, and pest infestation.
- **IoT-enabled Sensors**: Track soil pH, moisture, nutrient levels, and weather. These enable **precision irrigation and fertilization.**
- **Artificial Intelligence (AI) & Machine Learning (ML)**:
  - Predicts pest outbreaks.
  - Estimates crop yields.
  - Provides personalized recommendations for farmers.
- **Robotics and Automation**:
  - Autonomous tractors and robotic harvesters reduce labor shortages.
  - Drones are used for spraying, seeding, and crop monitoring.

- **Decision Support Systems (DSS)**:
  - Software that helps farmers plan irrigation, fertilizer use, and pest control schedules.

Smart farming ensures efficiency, sustainability, and climate resilience.

5. Applications and Benefits

1. **Enhanced Productivity**: ICT and smart farming tools ensure optimal input use, reducing losses and increasing yields.
   Example: Precision farming in the US has improved maize productivity by 15–20%.
2. **Climate-smart Agriculture**: By using weather forecasts and predictive models, farmers adapt to changing rainfall patterns and temperature fluctuations.
3. **Reduced Costs**: Drones and sensors minimize input wastage, lowering fertilizer, pesticide, and water usage.
4. **Improved Market Access**: Digital platforms link farmers directly to buyers, reducing the role of intermediaries.
5. **Food Safety and Traceability**: Blockchain ensures that supply chains are transparent, improving consumer confidence.
6. **Financial Services Access**: Digital platforms simplify credit, subsidies, and crop insurance processes.

6. Case Studies

- **e-Choupal (India)**: ITC's digital platform provides farmers with price trends, weather forecasts, and direct market access. It reduced dependence on middlemen and increased farmer incomes.
- **Digital Green (India, Africa)**: Uses participatory videos to share farming practices. Adoption rates of new technologies are significantly higher.
- **Precision Irrigation in Israel**: Israel's IoT-based drip irrigation systems allow farmers to irrigate with extreme efficiency in arid conditions, making Israel a global leader in water-efficient agriculture.
- **Climate Corporation (USA)**: Uses Big Data and AI to provide farmers with recommendations on planting, pest control, and fertilizer use, increasing profitability.

7. Challenges in ICT and Smart Farming

1. **Digital Divide**: Many smallholders lack access to smartphones, internet, or electricity.
2. **High Initial Investment**: Technologies like drones, robotics, and sensors are expensive for marginal farmers.
3. **Low Digital Literacy**: Farmers may not understand how to operate or interpret ICT tools.
4. **Data Privacy Concerns**: Ownership and misuse of farm data is a sensitive issue.

5. **Policy Gaps**: Lack of clear guidelines on digital platforms, blockchain integration, and AI in agriculture.

8. Policy Implications and Future Prospects

- **Government Initiatives**:
  Digital India, e-NAM, Kisan Call Centres, PM-Kisan Samruddhi Yojana promote digital access for farmers.
- **Public-Private Partnerships (PPP)**: Encourage technology companies to collaborate with cooperatives and NGOs.
- **Capacity Building**: Training programs to improve farmers' digital literacy.
- **Climate Resilience**: Integration of ICT with national climate policies for sustainable agriculture.
- **Affordable Technologies**: Focus on low-cost IoT devices and open-source platforms for small farmers

Conclusion:

ICT, digital agriculture, and smart farming are revolutionizing agriculture by turning it into a knowledge-intensive, technology-driven sector. While challenges like affordability, literacy, and infrastructure remain, the potential benefits far outweigh the risks. For smallholder farmers, especially in countries like India, ICT can bridge the information and resource gap, improve incomes, reduce risks, and ensure long-term sustainability. With the right policies, investments, and farmer training, digital agriculture can play a central role in achieving food security, rural prosperity, and climate resilience.

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PLANT GROWTH PROMOTING RHIZOBACTERIA: A STRATEGY FOR SUSTAINABLE CROP PRODUCTION

Anjan Kumar Sarma and Kanishka Purkait*

Faculty of Science, Assam down town University, Sankar Madhab Path,
Gandhi Nagar, Panikhaiti, Guwahati, Assam, India 781026

*Corresponding author E-mail: kanishkapurkait42@gmail.com

Abstract:

Plant Growth-Promoting Rhizobacteria (PGPR) offer an environmentally sustainable alternative to conventional chemical inputs, making them a major tool for advancing organic farming and sustainable agriculture. These beneficial microorganisms support plant growth through multiple mechanisms, including nutrient mobilization, phytohormone synthesis, and pathogen suppression. Their contributions to soil health, nutrient acquisition, and secretion of bioactive compounds are crucial for sustainable crop production. The transformation of PGPR into biofertilizers or bioinoculants has significant potential to reduce the dependency on synthetic chemicals. Given the rising global demand for food, minimising chemical use has become urgent, calling for innovative and sustainable agricultural approaches. PGPR mitigate abiotic stresses, promote plant vigor and assist in phytoremediation, offering pathways to reduce chemical inputs and improve soil quality. Continued research and field implementation are essential to exploit their potential fully. Overall, PGPR represent a promising, eco-friendly strategy for ensuring agricultural sustainability, food security and environmental protection.

Keywords: Biofertilizer, Solubilization, Rhizomicrobiome

Introduction:

Plant Growth Promoting Rhizobacteria (PGPR) are a diverse group of beneficial microorganisms closely associated with plants and known for enhancing plant health through multiple physiological and biochemical mechanisms (Daraz *et al.* 2023). As eco-friendly alternatives to agrochemicals, PGPR present a sustainable approach to crop protection and productivity enhancement (Santoyo *et al.* 2021). The extensive use of synthetic fertilisers and pesticides has been linked to environmental degradation and risks to human and animal health. By contrast, PGPR provide a non-toxic, sustainable option well suited to organic agriculture (Nagrale *et al.* 2023).

PGPR stimulate plant growth both directly and indirectly by improving nutrient availability, producing phytohormones, and providing protection against pathogens (Andrade *et al.* 2023). They act through diverse mechanisms, including phosphate solubilization, biological nitrogen fixation, rhizosphere engineering, quorum sensing, phytohormone production, antifungal activity, volatile organic compound emission, systemic resistance induction, promotion of beneficial symbioses, and interference with pathogen toxins (Bhattacharyya *et al.* 2012). Coinoculation of PGPR with rhizobia further enhances nodulation and symbiotic efficiency (Swarnalakshmi *et al.* 2020). Their interactions within the rhizosphere are shaped by various biotic and abiotic factors, influencing their effects on root systems (Vacheron *et al.* 2013). Many PGPR produce antimicrobial metabolites such as antibiotics, VOCs, and lytic enzymes that suppress phytopathogens, while their ability to competitively colonise the rhizosphere is critical for effective bioinoculant development (Santoyo *et al.* 2021). Additionally, PGPR modulate plant sugar levels and distribution through photosynthate metabolism (Su *et al.* 2024). By inducing immune responses and synthesising pathogen-antagonistic compounds, they provide dual benefits of disease control and growth promotion (Jiao *et al.* 2021). Their contribution to abiotic stress tolerance, including drought, salinity, and heat stress, is particularly relevant in the context of climate change (Backer *et al.* 2018).

Role of PGPR in plants

The presence of PGPR has been found to exhibit a significant correlation with both direct and indirect positive effects on plant growth. PGPR enhances plant growth through mechanisms such as the induction of systemic resistance, antibiosis, and competitive exclusion (Hashem *et al.* 2019). The interactions between plants and PGPR in the rhizosphere contribute to the maintenance of soil fertility and plant health (Vecchiato *et al.* 2021). Furthermore, PGPR actively interferes with quorum-sensing signals, preventing the formation of harmful bacterial biofilms around plant roots. In reciprocation, plants facilitate the competitive colonisation of PGPR in their niches (Hartmann and Anton, 2020). The pivotal role of PGPR in promoting plant growth encompasses diverse mechanisms, including conferring abiotic stress tolerance in plants, facilitating nutrient fixation for easy plant uptake, regulating plant growth through the production of plant growth regulators, synthesising siderophores, emitting volatile organic compounds, and producing protective enzymes such as chitinase, glucanase, and ACC-deaminase to prevent plant diseases (Choudhary *et al.* 2011). Moreover, the remediation of contaminated soils through the application of PGPR has been explored, highlighting the potential for PGPR to contribute to soil cleanup processes (Vaishnav *et al.* 2022)

Mechanism of action of PGPR in plant

PGPR enhance plant growth through direct and indirect mechanisms (Kloepper and Schroth, 1981). Direct promotion involves improving nutrient acquisition by fixing nitrogen, solubilising phosphate, and producing siderophores that enhance iron uptake. PGPR also regulate plant hormone levels such as auxins, gibberellins, cytokinins, and nitric oxide, influencing root architecture and nutrient absorption (Vessey *et al.* 2003). Indirect promotion occurs when PGPR act as biocontrol agents, protecting plants from pathogens by competing for nutrients and space, producing antifungal compounds, and inducing plant defense systems (Glick, 2012). They produce metabolites such as hydrogen cyanide, phenazines, pyrrolnitrin, 2,4-diacetylphloroglucinol, pyoluteorin, viscosinamide, and tensin, which suppress pathogens (Bhattacharyya and Jha, 2012). This interaction triggers induced systemic resistance, enhancing plant resilience.

Role of PGPR in mitigating abiotic stress

Plant Growth-Promoting Rhizobacteria (PGPR) are beneficial soil microorganisms that colonise the rhizosphere and enhance plant growth and productivity through diverse physiological and biochemical mechanisms. In recent years, their role in mitigating abiotic stresses such as salinity, drought, heavy metal toxicity, and extreme temperatures has gained significant attention due to their eco-friendly and sustainable nature (Grover *et al.* 2011; Vacheron *et al.* 2013). Under abiotic stress conditions, plants experience physiological disturbances such as reduced water uptake, nutrient imbalance, and oxidative damage. PGPR alleviate these stresses by modulating plant metabolism, enhancing antioxidant activity, and improving nutrient acquisition. Glick (2012). One of the major mechanisms through which PGPR confer stress tolerance is the production of phytohormones, including indole-3-acetic acid, gibberellins, cytokinins, and abscisic acid. These hormones regulate root architecture, increase water and nutrient absorption, and improve plant adaptability under adverse conditions (Egamberdieva *et al.* 2017). In addition to hormonal regulation, PGPR enhance antioxidant defence systems in plants. They stimulate the activity of key antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase, which detoxify reactive oxygen species generated during abiotic stress (Bhattacharyya and Jha, 2012). By reducing oxidative damage, PGPR help in maintaining cellular integrity and photosynthetic efficiency. Another important mechanism is the enhancement of nutrient availability in stressed soils. PGPR solubilise essential nutrients such as phosphorus, potassium, and zinc, and produce siderophores that chelate iron, making it available for plant uptake even under unfavourable conditions (Kumar *et al.* 2019). This improved nutrition strengthens plant physiological performance under stress. Moreover, PGPR induce systemic tolerance in plants through the modulation of stress-responsive phytohormones like salicylic acid, jasmonic acid, and abscisic acid, preparing the plant to respond more effectively to subsequent stress episodes (Yang *et al.* 2009). In the case of heavy metal stress, PGPR play a crucial role in detoxification and immobilisation of toxic metals such as cadmium (Cd), lead (Pb), aluminium (Al), and iron (Fe). They produce organic acids, siderophores, and biosurfactants that bind to metal ions, reducing their solubility and bioavailability in the rhizosphere (Ma *et al.* 2016). This not only protects plants from metal toxicity but also improves soil health by preventing metal leaching and contamination. PGPR act as natural bioinoculants that promote plant resilience against multiple abiotic stresses through a combination of physiological, biochemical, and molecular mechanisms. The integration of PGPR-based biofertilizers into crop management systems can significantly reduce dependence on chemical inputs and contribute to maintaining productivity under changing climatic conditions.

Application of PGPR for enhancing crop growth

The soil rhizomicrobiome assumes a pivotal role in agriculture due to the diverse array of root exudates and plant cell debris, attracting a varied and distinctive microbial colonisation (Backer *et al.* 2018). Over evolutionary time, plants have engaged microbes to aid in adapting to prevailing growing environments. Microbes, reciprocally, facilitate plant growth, obtaining nutrition from root exudates as a source of reduced carbon and creating a favourable habitat (Lyu *et al.* 2021). The rhizomicrobiome's microbial constituents actively participate in nutrient acquisition, assimilation, soil texture improvement, and the secretion and modulation of extracellular molecules, such as hormones, secondary metabolites, antibiotics, and various signalling compounds, collectively fostering plant growth. (Backer *et al.* 2018). The presence of specific bacterial species in rhizosphere soil serves as a biological indicator for assessing soil quality and fertility, with these bacteria being regarded as biofertilizers that do not compromise edaphic profiles and ecological sustainability (Adedayo *et al.* 2022)

Rhizosphere microbes, particularly beneficial rhizobacteria, possess the potential to be developed into biofertilizers or bioinoculants, contributing significantly to sustainable agricultural development (Liu *et al.* 2023). The coevolution of soil microbes with plants is essential for adapting to extreme abiotic environments, resulting in improved economic viability, soil fecundity, and environmental sustainability (Gouda *et al.* 2018). PGPR exhibit both synergistic and antagonistic interactions within the rhizosphere and bulk soil, indirectly enhancing plant growth rates (Vejan *et al.* 2016).

The escalating global population has led to a substantial increase in the demand for agricultural yield, prompting large-scale production of chemical fertilisers (Gouda *et al.* 2018). However, the challenge lies in meeting this demand while significantly reducing the use of synthetic chemical fertilisers and pesticides (Vejan *et al.* 2016). Agricultural production faces considerable threats such as poor soil quality, biotic and abiotic stresses, and changing climatic conditions, necessitating innovative approaches for sustainable practices (Majeed *et al.* 2018). Certain growth-promoting rhizobacteria have demonstrated the capability to colonise the rhizosphere and shield roots from the adverse effects of abiotic stressors (Khan *et al.* 2021). Abiotic stresses, including drought, salinity, heavy metals, and temperature variations, negatively impact plant growth, leading to an overall decline in plant development and productivity (Khan *et al.* 2021).

Various rhizobacteria and endophytes are recognised for promoting plant growth, residing within healthy plant tissues and inducing or promoting plant growth. (Lata *et al.* 2018). Rhizobacteria and mycorrhizae play a role in increasing stress tolerance by stimulating the secretion of phytohormones, reducing ethylene levels, and contributing to other physiological processes (Koza *et al.* 2022). Specific PGPR strains exhibit significant potential for phytoremediation of heavy metals and enhancing plant growth under stress conditions, particularly salinity and drought (Kazerooni *et al.* 2021). Rhizospheric bacterial strains contribute to plant growth by releasing phytohormones, solubilising phosphate, fixing nitrogen, synthesising ammonia, and producing antimicrobial products, thereby enhancing heavy metal remediation efficiency and promoting plant growth under adverse metal toxic conditions (Karthik *et al.* 2017).

PGPR has emerged as a crucial strategy in sustainable agriculture, offering the prospect of reducing reliance on synthetic fertilisers and pesticides while simultaneously promoting plant growth, health, and soil quality (Andrade *et al.* 2023). Mechanisms of PGPR action involve the regulation of hormonal and nutritional balance, induction of resistance against plant pathogens, and nutrient solubilization for easy plant uptake (Vejan *et al.* 2016). Beyond growth enhancement, plant growth-promoting rhizobacteria/fungi (PGPR/PGPF) can suppress plant diseases through the production of inhibitory chemicals and induction of immune responses in plants against phytopathogens (Saadony *et al.* 2021). PGPR with nitrilase activity has recently shown promise in addressing agricultural challenges (Lyu *et al.* 2021). The application of PGPR in agricultural production is gaining popularity due to its significant reduction in the use of chemical fertilisers and pesticides (Azizoglu *et al.* 2021). While PGPR has found extensive use in traditional agriculture, its application in soilless agriculture is limited. Soilless agriculture, favoured by commercial farmers, eliminates soilborne problems, maintaining a clean system (Azizoglu *et al.* 2021). Integrated efforts involving effective microbes alleviate the environmental burden of agrochemicals, simultaneously managing nutrient availability. PGPR-assisted modern agriculture practices represent a sustainable and environmentally friendly approach to enhance farming without compromising crop yield (Kumawat *et al.* 2023)

Conclusion:

PGPR play a vital role in sustainable agriculture by enhancing crop growth, nutrient uptake, and stress tolerance while reducing the reliance on synthetic fertilisers and pesticides. Their integration into agricultural systems can improve soil health, boost crop yield and mitigate the effects of climate change. This microbial approach provides a practical and eco-friendly strategy to address global challenges of food security and environmental degradation. Future research and field-scale applications are essential to fully exploit the benefits of PGPR and realise their potential as key components of resilient and sustainable farming systems.

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A REVIEW ON BIOCHEMICAL AND NUTRITIONAL CHARACTERIZATION OF SELECTED SOLANACEOUS VEGETABLES

Bipasha Mridha Ghosh*, Rupsha Roy, Parathirta Das and Digangana Basu

NSHM Knowledge Campus, Durgapur-713212

*Corresponding author E-mail: bipasha.mridha@nshm.com

Abstract:

The Solanaceae family, also known as the nightshade family, includes several economically and nutritionally vital vegetables such as tomato (*Solanum lycopersicum*), eggplant (*Solanum melongena*), chili (*Capsicum annuum*), and potato (*Solanum tuberosum*). These vegetables are rich in macronutrients, micronutrients, and bioactive compounds such as alkaloids, carotenoids, flavonoids, and phenolic acids, all of which play crucial roles in human nutrition and health. This review highlights the biochemical and nutritional composition of selected Solanaceous vegetables, emphasizing their antioxidant, antimicrobial, and therapeutic potentials. The discussion also explores recent advances in biochemical analysis, biofortification, and the implications of these vegetables in sustainable food systems. Understanding the biochemical diversity of Solanaceae members provides valuable insights into their applications in functional food development and human health promotion.

Keywords: Solanaceae, Biochemical Composition, Nutritional Value, Antioxidants, Phytochemicals, Functional Foods

1. Introduction:

The Solanaceae family comprises about 90 genera and nearly 3,000 species distributed worldwide, with several species being important sources of food and medicine (Daunay *et al.*, 2008). The most cultivated Solanaceous vegetables include tomato, eggplant, chili pepper, and potato. These crops contribute significantly to global vegetable production and form an integral part of human diets due to their diverse nutritional and biochemical profiles (FAO, 2023).

Tomatoes are renowned for their lycopene content, an antioxidant carotenoid that reduces the risk of cardiovascular diseases and certain cancers (Giovannucci, 2002). Eggplants are rich in phenolic compounds, notably chlorogenic acid and nasunin, which contribute to their antioxidant activity (Sadilova *et al.*, 2006). Chili peppers contain capsaicinoids responsible for their pungency and health-promoting properties, including anti-inflammatory and analgesic effects (Zimmer *et al.*, 2012). Potatoes, though often considered starchy foods, are a major source of carbohydrates, potassium, and vitamin C (Burlingame *et al.*, 2009). The biochemical and nutritional characterization of Solanaceous vegetables provides a foundation for understanding their roles in human health, crop improvement, and functional food development.

2. Biochemical Composition of Solanaceous Vegetables

2.1 Carotenoids

Carotenoids are essential pigments found in high concentrations in tomatoes, red peppers, and certain eggplants. Lycopene, β-carotene, and lutein are among the most studied carotenoids in these vegetables (Rao & Rao, 2007). Lycopene, in particular, is a potent antioxidant that scavenges singlet oxygen and free radicals, thereby reducing oxidative stress in the human body.

2.2 Phenolic Compounds

Phenolics, including flavonoids, tannins, and phenolic acids, are secondary metabolites that play major roles in color, flavor, and antioxidant defense. Eggplants are especially rich in chlorogenic acid and nasunin, which protect lipids and DNA from oxidative damage (Mishra *et al.*, 2012). The total phenolic content varies across species, influenced by genetic and environmental factors.

2.3 Alkaloids

Alkaloids are nitrogen-containing compounds characteristic of Solanaceae members. While some alkaloids such as solanine and solasodine can be toxic at high concentrations, they also possess pharmacological benefits (Friedman, 2006). Capsaicin, the major alkaloid in chili peppers, exhibits anti-obesity, antioxidant, and antimicrobial activities (Luo *et al.*, 2011).

2.4 Vitamins and Minerals

Solanaceous vegetables are excellent sources of essential vitamins and minerals. Tomatoes and peppers provide abundant vitamin C and provitamin A, while potatoes supply vitamin B6, potassium, and magnesium (Burlingame *et al.*, 2009). These micronutrients are crucial for immune regulation, nerve function, and metabolic processes.

3. Nutritional Characterization

3.1 Macronutrients

Potatoes are a staple carbohydrate source, containing approximately 70–80% water, 15–20% carbohydrates, and 2% protein (Navarre *et al.*, 2009). Eggplants and tomatoes are low in fat and calories, making them suitable for calorie-conscious diets (Kashyap *et al.*, 2021).

3.2 Micronutrients

Tomatoes contain 20–40 mg of vitamin C per 100 g and 2–4 mg of lycopene per 100 g of fresh weight (Giovannucci, 2002). Peppers are rich in β-carotene, while eggplants contain phenolic antioxidants that help regulate cholesterol levels (Mishra *et al.*, 2012).

3.3 Antioxidant Capacity

The antioxidant capacity of Solanaceous vegetables is attributed to the presence of phenolics, carotenoids, and vitamins. Studies show that extracts from tomato and eggplant reduce lipid peroxidation and protect against oxidative damage (Sadilova *et al.*, 2006; Rao & Rao, 2007). These compounds play preventive roles in chronic diseases such as diabetes, cancer, and cardiovascular disorders.

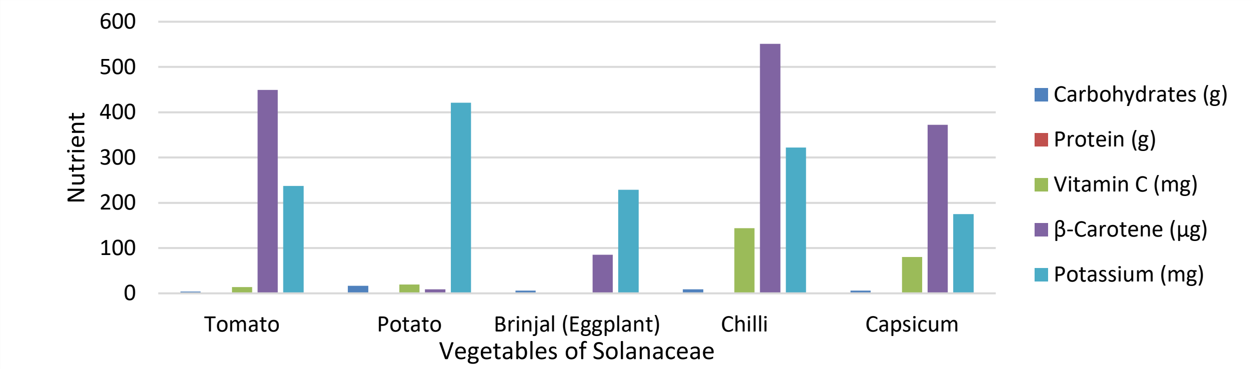

Figure 1: Bar Graph: Comparative Nutrient Composition of Selected Solanaceous Vegetables (per 100 g)

This bar graph can visually compare macronutrient and micronutrient levels across Solanaceous vegetables — highlighting Vitamin C richness in chilli **and** high carbohydrate content in potato.

Table 1: Biochemical Composition of Selected Solanaceous Vegetables (per 100 g edible portion)

Vegetable	**Tomato (*Solanum lycopersicum*)**	**Eggplant / Brinjal (*Solanum melongena*)**	**Chili Pepper (*Capsicum annuum*)**	**Potato (*Solanum tuberosum*)**
Major Carotenoids	Lycopene (2–4 mg), β-carotene (0.8 mg), Lutein (0.1 mg)	β-carotene (0.04 mg), Lutein (0.03 mg)	β-carotene (3–5 mg), Capsanthin, Capsorubin	Lutein (0.03 mg), Zeaxanthin (0.02 mg)
Phenolic Compounds / Flavonoids	Caffeic acid, Chlorogenic acid, Rutin	Chlorogenic acid (50–90 mg), Nasunin (anthocyanin)	Quercetin, Apigenin	Chlorogenic acid (25–60 mg), Catechin
Alkaloids	Tomatine (trace)	Solasodine (trace)	Capsaicin (0.1–1%)	Solanine (2–10 mg, reduced by cooking)
Vitamins	Vit. C (20–40 mg), Vit. A (42 µg), Vit. K (7 µg)	Vit. C (2.2 mg), Folate (22 µg)	Vit. C (140 mg), Vit. A (59 µg), Vit. E (0.7 mg)	Vit. C (19 mg), Vit. B6 (0.3 mg), Folate (15 µg)
Minerals (mg/100 g)	K (237), Mg (11), Fe (0.5)	K (230), Mg (14), Fe (0.3)	K (322), Mg (23), Fe (1.0)	K (421), Mg (23), Fe (0.8)
Other Bioactive Compounds / Notes	High antioxidant activity; anti-cancer and cardioprotective effects	Rich in anthocyanins; antioxidant and lipid-lowering properties	Strong antioxidant; anti-inflammatory and metabolic stimulant	Source of complex carbs, resistant starch; antiox
References	Giovannucci (2002); Rao & Rao (2007)	Sadilova *et al.* (2006); Mishra *et al.* (2012)	Zimmer *et al.* (2012); Luo *et al.* (2011)	

4. Health benefits of solanaceous vegetables

Table 2: Health Benefits of Selected Solanaceous Vegetables

Vegetable	Major Bioactive Compounds	Primary Health Benefits	Mechanism / Mode of Action	Supporting References
Tomato (*Solanum lycopersicum*)	Lycopene, β-carotene, Vitamin C, Flavonoids	• Reduces risk of cardiovascular diseases • Protects against prostate and breast cancer • Enhances immune function	Antioxidant and anti-inflammatory activity; scavenges reactive oxygen species (ROS); reduces LDL oxidation	Giovannucci (2002); Rao & Rao (2007)
Eggplant / Brinjal (*Solanum melongena*)	Chlorogenic acid, Nasunin (anthocyanin), Polyphenols	• Lowers cholesterol and blood pressure • Protects against liver damage • Prevents oxidative stress	Chelation of free radicals and lipid peroxidation inhibition; improves lipid metabolism	Sadilova *et al.* (2006); Mishra *et al.* (2012)
Chili Pepper (*Capsicum annuum*)	Capsaicin, β-carotene, Vitamin C, Flavonoids	• Promotes weight loss and metabolism • Provides pain relief • Exhibits antimicrobial and anticancer properties	Stimulates thermogenesis and endorphin release; inhibits pro-inflammatory mediators; induces apoptosis in cancer cells	Zimmer *et al.* (2012); Luo *et al.* (2011)
Potato (*Solanum tuberosum*)	Vitamin C, Potassium, Chlorogenic acid, Dietary fiber	• Supports heart health and nerve function • Provides antioxidant protection • Aids digestion and satiety	Reduces oxidative stress; maintains electrolyte balance; promotes gut health	Burlingame *et al.* (2009); Friedman (2006)
Sweet Pepper / Bell Pepper (*Capsicum annuum var. grossum*)	Capsanthin, β-carotene, Vitamin A, Vitamin E	• Enhances vision and skin health • Strengthens immune system • Prevents cellular oxidative damage	Antioxidant carotenoids scavenge free radicals and boost collagen synthesis	Kashyap *et al.* (2021); Verma & Singh (2022)

4.1 Cardiovascular protection: Regular consumption of tomatoes and peppers improves vascular health and reduces LDL cholesterol levels due to the synergistic effects of lycopene, vitamin C, and flavonoids (Giovannucci, 2002).

4.2 Anticancer properties: Bioactive compounds such as lycopene, chlorogenic acid, and capsaicin have been shown to modulate oxidative pathways, inhibit cell proliferation, and induce apoptosis in cancer cells (Luo *et al.*, 2011; Mishra *et al.*, 2012).

4.3 Anti-inflammatory and antimicrobial activity: Capsaicin inhibits pro-inflammatory mediators and has shown antimicrobial activity against pathogens like *E. coli* and

Staphylococcus aureus (Zimmer *et al.*, 2012). Similarly, phenolics in eggplant and tomato exhibit anti-inflammatory properties.

4.4 Role in eye and skin health: Vitamin A precursors and β-carotene in chili and tomato promote visual health, while vitamin C and polyphenols support collagen synthesis and skin repair (Rao & Rao, 2007).

5. Anti-nutritional factors

Despite their nutritional benefits, Solanaceous vegetables contain certain anti-nutritional compounds such as glycoalkaloids (solanine, chaconine), which can be toxic if consumed in large quantities (Friedman, 2006). Proper cooking and processing methods can significantly reduce their levels. Similarly, excessive intake of capsaicin can irritate mucous membranes, though moderate consumption is beneficial.

6. Recent advances and applications

Biotechnological approaches such as genetic modification and CRISPR-Cas9 have been employed to enhance carotenoid biosynthesis and reduce glycoalkaloid toxicity in Solanaceous crops (Li *et al.*, 2018). Metabolomic profiling is increasingly used to assess biochemical diversity and improve nutritional quality (Kashyap *et al.*, 2021). Waste biomass valorization from tomato peels and potato skins has emerged as a sustainable source of antioxidants and dietary fibers (Verma & Singh, 2022).

These innovations not only improve the nutritional profile of Solanaceous vegetables but also contribute to food security and sustainable agriculture.

Conclusion:

Solanaceous vegetables are a cornerstone of human nutrition, offering a wide array of macro- and micronutrients along with bioactive compounds that promote health and prevent diseases. Their biochemical diversity, rich antioxidant capacity, and therapeutic potential make them vital to both traditional diets and modern functional food industries. Ongoing research in genetic enhancement, metabolomics, and sustainable utilization of by-products will further amplify their nutritional and economic value. Future studies should focus on standardizing biochemical markers and optimizing cultivation conditions for improved nutritional outcomes.

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COLD STRESS IN CROP PLANTS: PHYSIOLOGICAL IMPACTS, ADAPTIVE MECHANISMS AND BREEDING STRATEGIES FOR ENHANCED TOLERANCE

Raghavendra V C*[1], Prem Sagar S P[1], Yashaswini R[1],
Sridhara M R[1], Akshay Kumar Kurdekar[2] and B V Sinchana[2]
[1]University of Agricultural Sciences, Raichur - 584104 (Karnataka), India
[2]University of Agricultural Sciences, GKVK, Bengaluru - 560065 (Karnataka), India
*Corresponding author E-mail: raghuvcagri@gmail.com

Introduction:

Temperature is a key abiotic signal that regulates plant function throughout development. Alterations in growth temperature act as a stimulus to initiate metabolic changes and promote developmental switches. Plants exhibit a maximum rate of growth and development at an optimum temperature or over a diurnal range of temperatures (Fitter and Hay, 1981). It depends on genotype of an individual and stage of growth, development of an individual

Temperature stress like heat stress, freezing stress and chilling stress cause negative impact on respiration, fertilization, photosynthesis, protein confirmation, membrane composition and stability and heat shock and cold response proteins in plants. Low temperature is a major abiotic stress that limits the growth, productivity and geographical distribution of agricultural crops and can lead to significant crop loss. There are two types of low temperature stress in plants chilling stress and freezing stress. Chilling low temperature occurs when temperatures are lowered to 10 to 15 °C, whereas the freezing low temperature occurs when temperatures are lowered to 0 °C and ice forms within the tissues.

The Chilling and freezing to low temperatures leads to disturbances in all physiological processes water regime, mineral nutrition, photosynthesis, respiration and metabolism. Inactivation of metabolism, observed at chilling-sensitive plants is a complex function of both temperature and duration of exposure. Response of plants to low temperature exposure is associated with a change in the rate of gene transcription of a number of low molecular weight proteins.

To cope with low temperature, plants have evolved a variety of efficient mechanisms that allow them to adapt to the adverse conditions. This adaptive process involves a number of biochemical and physiological changes, including increased levels of proline, soluble sugars and MDA, as well as enzyme activities. Many economically important crops, such as cotton, soybean, maize, rice, tomato, and many tropical and subtropical fruits, are classified as chill sensitive. Temperate crops are chilling resistant but they are sensitive to freezing temperature

Symptoms of chilling injury

- Reduced plant growth and death
- Surface lesions on leaves and fruits
- Abnormal curling, crinkling of leaves
- Water soaking of tissues
- Cracking, splitting and dieback of stems
- Failure to fruit set and pollen sterility.
- Loss of vigour
- Chlorosis, necrosis in plants
- Stem injury, collapse and complete wilting of plants

Chilling symptoms in fruits

- Sunken pits in cucumber
- Browning of skins and degradation of pulp tissue in banana
- Blackheart of pine apple (Wilson, 1987)

Adaptation and acclimation to low temperature

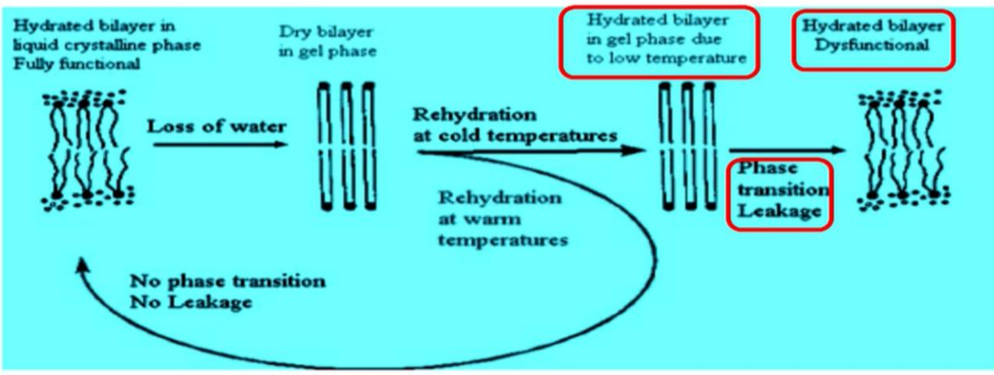
Morphological and life cycle adaptions in the evergreen trees of temperate trees of the plants have to face freezing stress during most of the time. The 10th year of evergreen conifers and broad-leafed evergreen have wax coated leaves so that they are protected in winter from desiccation. The conifers have small narrow needle like leaves in spruces, spines or scales leaves in case of saddam and cypress, which reduce the surface area to reduce transpiration of water and risk of freezing.

The presence of terpenoids and alcohol in the xylem sack which prevent freezing of water an important adaption shown by plants growing in temperate region. It is their ability to retain water within plant tissues in super cold gel like state by which ice formation due to new creation is prevented. Another gap adaption involves the termination of growth activity during winter cold acclimation is a plants ability to reversely adjust their metabolism to survive in the changing weather. The annual plants like rye adjust their metabolism during the winter months to enable them to cope with cold stress.

Different physiological processes induced as a consequence of plant acclimation to cold

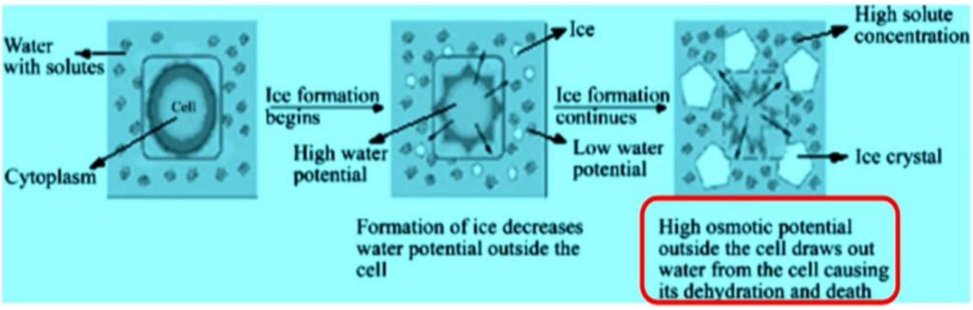
Most temperate plants can acquire tolerance to freezing temperature by a prior exposure to low nonfreezing temperature, a process known as cold acclimatization. Cold acclimation it induces the accumulation of cryoprotectants like sugars, proline, Ca^{2+}, ROS, activation of scavenge system and changing gene expression, protein synthesis and modification in plant membranes these causes change in lipid composition and it increases the desaturated fatty acids, fluidity of membranes these leads to reduction of lower threshold temperature in acclimated plants.

Modification of plant cell membranes under low temperature stress



Membranes are a primary site of cold-induced injury. Hydrated bilayer is fully functional in liquid crystalline phase, if loss of water occurs in this phase it leads to dry bilayer in gel phase. During this phase rehydration occurs at warm temperature leads to no phase transition and no leakage and it undergoes liquid crystalline phase becomes fully functional membrane. If rehydration occurs at low temperature leads to phase transition and leakage of membranes and membranes becomes dysfunctional.

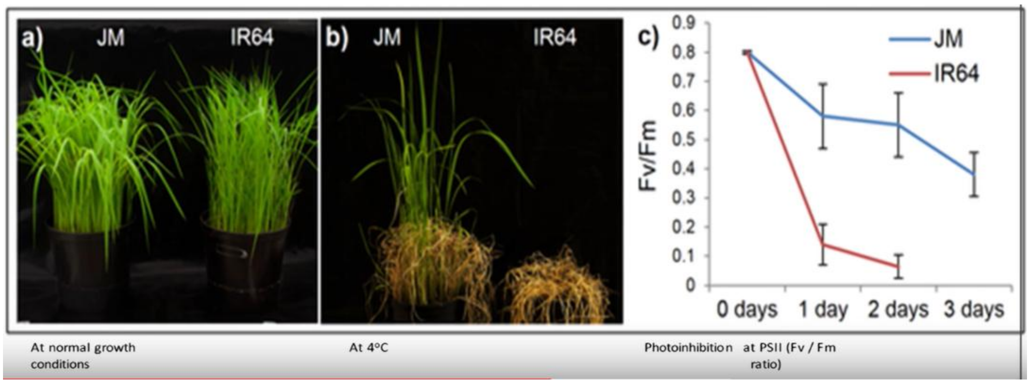
Osmotic response under low temperature tolerance



The osmotic stress due to ice formation at low temperature metabolic activity is arrested or is reduced. It is due to loss of enzyme activity at low temperatures. Under low temperature stress conditions the plant cells are exposed to low temperature. When the cells are exposed to low temperature ice formation takes place around the cell and this formation of ice leads to decrease in water potential outside the cells. If ice formation is continuous causes high osmotic potential outside the cell and draws out water from the cell leads to dehydration and death of cell.

Photo inhibition under low temperature stress

Photo inhibition in Rice genotypes seeds to low temperature. Cold stress acclimation in jumla marshy (JM) and IR64 genotypes of rice is shown in figure. JM and IR 64 seedlings were grown for 3weeks under regular growth conditions and then moved to 4°C cold conditions. After 3days in cold conditions plants were moved back to regular growth conditions and allowed to recover for 2weeks. In fig (a) plants are seen which are just before cold exposure .Fig(b) cold treated plants after recovery for 2weeks. Fig (c) represents chlorophyll V by M ratio in JM and IR64 cold stress exposure.



JM – Cold tolerant **IR-64** –cold susceptible.

Extracellular ice formation

- ✓ Ice formation in the intercellular spaces of tissues.
- ✓ Extracellular ice formation increases the concentration of extracellular solutes, as a result, water is withdrawn from the cells during extracellular ice formation.
- ✓ This creates water stress in the frozen tissues/ plants.

Intracellular ice formation

- ❖ Within the cell ice crystal formation.
- ❖ Intracellular ice crystal formation is the major and terminal freezing stress and it is likely cause of lethality, since it causes physical disruption of intracellular structures by ice crystals.

Super cooling

- ❖ Cooling of water below 0 °C without ice formation is called super cooling.
- ❖ Also known as undercooling or sub cooling.
- ❖ Super cooling inhibits the formation of ice within the tissue by ice nucleation and allows the cells to maintain water in a liquid state.
- ❖ Regarded as a major mechanism of freezing avoidance.

Use of anti-freeze proteins as ice nucleators

- ❖ AFPs provide freezing tolerance to snowdrop plants.
- ❖ AFPs are secreted by cells and block ice nucleation in intercellular spaces.
- ❖ AFPs have been purified from over 15 plants, including gymnosperms, dicots and monocots.

Frost plasmolysis

- ❖ Contraction of the dead protoplast, leaving a large space between it and its cell wall.
- ❖ Freeze killed cells or death cells characteristically show frost plasmolysis.

Vapor pressure concept

- ❖ There is an accelerated decrease in vapor pressure of water in the frozen state with drop in temperature.

Eutectic point.

- ❖ A point at which all the solute crystallizes and, therefore, remaining water in the absence of solute also solidifies.

Double freezing point

- ❖ It signifies two freezing points where in, the first freezing point is due to freezing of extracellular water, while the second is due to freezing of intracellular water**.**

Secondary freezing injury

1. Freeze-smothering: Plants injured due to an ice covering are said to suffer smothering injury. It creates secondary stress by disruption of normal respiration due to gas stress rather than a primary effect of ice.

2. Freeze-desiccation: Winter injury associated with reduced transpiration rate accompanied with increased cell sap concentration, since translocation of water is impossible due to freezing translocating vessels.

3. Freeze dehydration: When ice forms extracellularly, it dehydrates the water from the cell leading to a secondary water-stress called freeze dehydration strain.

Stress due to external factors

1. Ice sheet formation in the field above and below the ground.
2. Plant tissues killed during freeze-thaw are highly prone to pathogen attacks.
3. Surviving cells or tissues may be subject to auto toxicity produced by dead cells of the surrounding tissues.

Mechanisms of low temperature tolerance

A. Chilling tolerance mechanisms

1. Membrane-lipid unsaturation
2. Reduced sensitivity of photosynthesis
3. Increased chlorophyll accumulation
4. Improved germination
5. Improved fruit or seed set
6. Pollen fertility

Ability of some genotypes to survive or perform better under chilling stress than other genotypes is called chilling tolerance.

1. Membrane-lipid unsaturation: Chilling tolerant varieties show a high degree of membrane lipid unsaturation than do susceptible varieties. As increase in lipid unsaturation in membranes, increase the tolerance to chilling stress.

2. Reduced sensitivity of photosynthesis: Chlorophyll and photosynthesis are major sites of chilling injury. Some of photosynthesis specific enzymes interact with membranes and reduces the sensitivity of photosynthesis and increase the chilling tolerance

3. Increased chlorophyll accumulation: Low temperature inhibits the chlorophyll accumulation in actively growing leaves. Ex: Japonica rice accumulates more chlorophyll than Indica rice under cold stress conditions. So increase in chlorophyll accumulation in an actively growing tissues increases the cold tolerance.

4. Improved germination: This is most extensively studied aspect of chilling tolerance. Genetic variation in chilling tolerance at germination is known in many crops ex: soybean. Tolerance seeds of soyabean imbibed less water at 2.5 °C and seeds that had matured at lower temperature were more tolerant.

5. Improved fruit or seed set: Chilling tolerance at flowering is expressed as improved fruit or seed set and pollen fertilization. Chilling tolerance in plants depend on floral structure of plants Ex: Tolerance in rice was associated with larger anthers and stigmas.

6. Pollen fertility: Meiosis in anthers is the most susceptible to chilling stress. Ex: In case of sorghum high proline content of pollen shows chilling tolerance and increases the pollen fertility under cold stress conditions

Freezing tolerance mechanisms

1. Osmotic adjustment
2. Bound water
3. Plasma membrane stability
4. Cell wall properties
5. Cold responsive proteins

1. Osmotic adjustment: In most hardy plants cellular solutes increase during hardening by this they avoid intracellular ice formation as well as cellular dehydration. Ex: In cereals fructans become converted to fructose and sucrose during freezing stress and this induces tolerance to freezing.

2. Bound water: A part of cell water is bound in such a way that it does not participate in osmotic response. Bound water increases freezing tolerance by producing normal range of osmotic potential in hardy crop plants.

3. Plasma membrane stability: During freeze hardening plasma fluidity increases and reduces the freezing injury. Increased stability of plasma membrane prevents extension of ice formation to intracellular water, supercooling of the solution takes place in cells and reduces freezing temperature of cells.

4. Cell wall properties: When intercellular space is limited water freezing is affected by the size of cell wall micro capillaries. Xylem mucilages of cell wall inhibits the kinetics of the freezing process. Ex: Rye mucilage induces tolerant freezing stress.

5. Cold responsive proteins: A number of proteins are produced in response to low temperature these are called cold responsive proteins. Ex: In solanum sp. ABA proteins are accumulate in response to freezing stress.

Genetic resources for low temperature tolerance

1. Cultivated varieties
2. Germplasm lines
3. Cold tolerant mutants
4. Related wild species
5. Transgenes
6. Somaclonal variants.

Crop	Wild relative
Wheat	*Agropyron sp.,* Rye
Barley	*H. jubatum,*
Oats	*Avena sterilis*
Potato	*Solanum acaule, S. vernei.*

Breeding strategies to overcome cold stress in crop plants

Selection trait: Germination

- ❖ An index of selection for chilling tolerance.
- ❖ Germination is divided into three phases:
- ❖ The largest effects of cold temperature during germination seem to be associated to the imbibition phase, considered the most sensitive.
- ❖ Cold temperature during this phase leads to increasing escape of solutes from the seeds, such as amino acids and carbohydrates, which has been attributed to the incomplete plasma membrane of the dry seed and to the disturbance caused on its reconstruction during imbibition phase by cold temperature.

Wang*, et.al* presented an article on GMFD3A gene enhances seed germination rate under low temperature in rice. The GMFAD3A gene was cloned from Soybean and then transformed into *Oryza sativa* sp Japonica by constitutive ubiquitin promoter via on *Agrobacterium tumefaciens* mediated transformation. Here they considered 2 varieties WT and Transgenic varieties, when these 2 varieties are subjected to 28℃ they showed 100% germination. But when they are exposed to 15 ℃, WT showed 19% germination and Transgenic verities showed more than 70% germination. So here we can conclude that GMFAD3A gene enhances seed germination under cold stress conditions.

Selection trait: Growth under chilling stress

Measured as plant dry matter accumulation. Commonly used indicator of chilling tolerance. This criterion is useful in the evaluation of germplasm lines and lines isolated from crosses, but not be applied for segregating populations. Yan *et al.* presented an article on effect of chilling stress on the growth rice of seedlings. Here 6 day old etiolated seedlings treated with

28 °C, 18 °C and 12 °C for 48hr in light. From this we can conclude that breeding for these traits will improve the productivity of crops and resistance to low temperature stress conditions.

Selection trait: Chlorophyll loss under chilling stress

In some species, e.g., rice, cucumber, tomato etc., chilling stress leads to a severe loss of chlorophyll.

Selection trait: Membrane stability

Parameter – Solute leakage from tissues upon rehydration, which is measured conduct metrically.

High leakage rates were induced during cold rehydration than drought rehydration. The low temperatures interfere with membrane expansion, possibly by lowering elasticity and hindering the incorporation of lipid material into the expanding membrane. The expansion of tissues at low temperatures may cause lesions in cellular membranes, contributing to chilling injury.

Selection trait: Pollen fertility

Parameter – Pollen sterility in chill stressed plants.

Meiotic stage of PMC is extremely sensitive to chilling. Cold stress at reproductive stage induces pollen sterility in susceptible plants. Low temperature reduces the activities of enzyme responsible for transport of hexose sugars to the tapetum and microspores. Reduced supply of sugars results in starvation of developing microspores and causes pollen sterility.

Selection trait: Freezing of isolated crowns

Parameter – Scoring recovery of isolated crowns after freezing.

In case of cereals isolated crowns are subjected to freezing, thawed and their recovery and regrowth is assayed.

Transgenic, as an approach of improvement

Biotechnology offers new strategies that can be used to develop transgenic crop plants with improved tolerance to cold stress. A number of genes have been isolated and characterized that are responsive to freezing stress.

Gene (s)	Origin of genes	Transgenic Plant
GmFAD3A	*Glycine max*	Rice
cox	*Arthrobacter pascens*	*A. thaliana*
codA	*Arthrobacter globiformis*	Rice
BADH	*Hordeum vulgare*	Rice
SCOF1	*Glycine max*	Potato
ala3	Chemically synthesised	Tobbaco

Mutation breeding

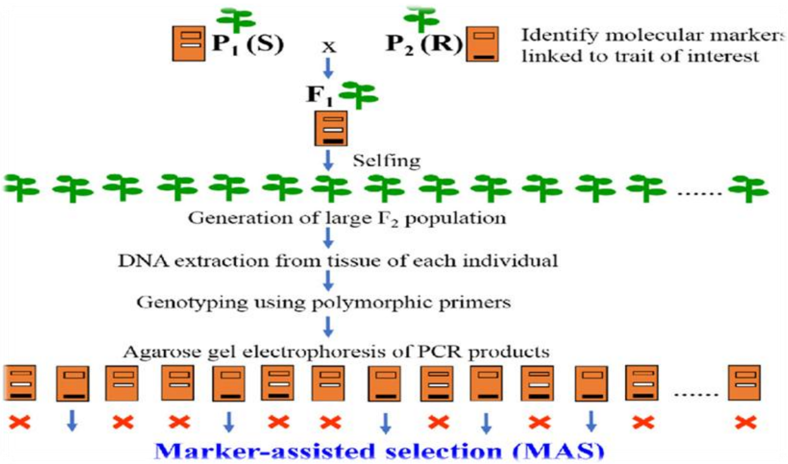
The process of exposing seed to chemicals or radiation in order to generate mutants with desirable traits. Gamma rays are the potential mutagenic agents, which can be utilized for improving the cold tolerance.

Mutant varieties

Variety/hybrid	Crop
yuangeng 1,2	wheat
Albidum 12	wheat
M112, M114	Wheat
Xinmu1	Alfalfa
Rajendra masoor 1	Lentil

Marker assisted selection

It is an indirect selection process where a trait of interest is selected based on a marker linked to a trait of interest rather than on trait itself. MAS approach can be used to identify genetic polymorphisms closely associated to cold adaptation among populations and selection for increased tolerance to freezing (TF).



Cold stress-related genes in plants

Genes	Species
FDA2-3	*Gossypium hirsutum*
Sb08g007310	*Sorghum bicolor*
AtGRXS17	*Solanum lycopersicum*
MYBS3	*Oryza sativa*
SET, JmJC	*Brassica rapa*
TaTPS11	*Triticum aestivum*
VvCBF	*Vitis vinifera*

Conclusion:

Cold stress poses a major challenge to global agriculture, significantly affecting crop growth, development and yield, particularly in temperate and high-altitude regions. Plants respond to low-temperature stress through a complex network of physiological, biochemical and molecular mechanisms that include membrane stabilization, osmotic adjustment, accumulation of cryoprotectants and activation of cold-responsive genes. The integration of conventional breeding, molecular genetics and biotechnological approaches such as transgenic development and marker-assisted selection has opened new avenues for enhancing cold tolerance in crops. Identifying and utilizing tolerant germplasm, wild relatives and functional genes can accelerate the breeding of resilient cultivars. Moving forward, a holistic strategy combining genomics, phenomics and climate-smart breeding will be crucial to develop high-yielding, cold-tolerant varieties capable of sustaining productivity under fluctuating climatic conditions, thereby ensuring global food and livelihood security.

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POST-HARVEST TECHNOLOGY OF NEEM

P. Sudha*, B. Nilashireen and P. Preetha
Tamil Nadu Agricultural University, Coimbatore
*Corresponding author E-mail: sudha.p@tnau.ac.in

Introduction:

Neem (*Azadirachta indica)* is an evergreen, temperature tolerant, flowering plant. Neem is one of the most valuable trees. The word 'Neem' is derived from the Sanskrit "NIMBA" which means "to bestow health" which signifies the great therapeutic value of this plant. The Sanskrit name of Neem is also *Arishtha* meaning the reliever of the sickness. The neem plant is rich resource has novel drug compounds, as plant derived medicines which have made large contributions to human health and well-being. Neem considered as a global natural product which plays an important role in solving health problems, an alternative to synthetic chemical pesticides and feed for livestock. Neem is the most useful traditional medicine as a source of many therapeutic agents in the Indian culture and grows well in the tropical and semi-tropical countries. In indigenous system of medicine, every part of neem tree is used, viz. bark, leaves, fruits, seeds and extracts. Its extracts have antiviral, antibacterial, antifungal, anthelmintic, antiallergic, antidermatic and anti-inflammatory properties. Neem is also termed as "free tree of India", "wonder tree", "Nature's drug store", Village dispensary", "Divine tree", "heal all" and "Panacea of all Diseases". In modern era, special emphasis should be on control of diseases of human as well as animals using non-toxic herbal products.

Neem tree seeks attention worldwide due to its medicinal properties in the field of Ayurveda and presence of azadirachtin ($C_{35}H_{44}O_{16}$) a tetranortriterpenoid which plays an important role in pest control activities. The bark, leaves, root, flower and fruit are rich in medicinal properties and also contain bio active components like Azadirachtin, Nimbin, Nimbinin, Nimbidin, Palmitic acids, Quercetin and other limonoids that has antioxidant, antimicrobial, antifungal properties which plays a significant role in the field of Ayurveda and pest control activities. Every part of the tree has been used as traditional medicine for household remedy against various diseases. It elaborates a vast array of biologically active compounds that are chemically diverse and structurally variable with different ingredients isolate from different parts of the tree. The active ingredients include alkaloids, flavonoids, phenolic compounds, carotenoids, steroid and ketones, which have anthelminthic, antimicrobial, antiulcer, antifertility, antidiabetic, anti-inflammatory and antitumor properties and Wound healing effects. The plant is used in combination with oil for more effectiveness to reduce toxicity level.

Nowadays, drug resistance is the main problem in both animals and humans due to use of synthetic products for long period of time which makes this plant to be preferable as alternative to overcome the situation. The products of neem tree are used for urinary tract isorders, eye disorders, diabetes, wound, and leprosy. The neem seeds are used in curing leprosy and intestinal worms. The stem, root bark, and fruit are used as a tonic and astringent. Besides the therapeutic values it can also be used as mosquito repellent, skin softener and insecticide. In addition, the tree is also source of feed for animals which is providing a number of nutrients like protein, minerals, fatty acids, vitamins. This implies that they are acquiring the medicine indirectly and become resistance toward diseases. It is effective against microorganism and ectoparasites including bacteria, fungi, viruses. The neem seed oil has toxicity effect against ticks and mites which are common on cattle, sheep, goats, wild ungulates and dogs. Alcohol and aqueous extracts of flowers of the tree also effect against cattle fila rial parasite.

The plant debris (after oil extraction) are potential source of organic manure and leaves could be used as a source for the preparation of fertilizer and pesticides to increase crop production. Instead of killing the pests, it affects their life cycle. Antifeedant properties found in neem compounds helps to protect the plants when applied on them and also it is being used to manufacture bioinsecticide that is environmentally friendly and do not have any side effect effects on plants and soil. Neem seed addresses problems related to health and can also be used as biopesticides, manures and fodder for animals. the most important use for neem products is to fight against crop pests and diseases. Neem means big money in the West and business sources estimate it has the potential to capture US$ 500 million shares of the US$ 6 billion annual pesticide market.

Neem tree

Neem, is native of India and growing in most of tropical and subtropical countries. According to Neem Foundation, India has around 20 million neem trees. Presently it can be seen growing successfully in about 72 countries worldwide, in Asia, Africa, Australia, North, Central and South America. It requires little water and plenty of sunlight to growing. It can grow up to 15 to 20 m tall (max up to 35 to 40 m) and requires annual rainfall between 400 and 1200 mm. It can also grow in regions with annual rainfall below 400 mm, but it depends largely on ground water levels in such situation.

Neem can grow in mostly different types of soil, but it grows well in drained deep and sandy soils. It is mainly a tropical to subtropical tree and grow at annual mean temperatures of 21 - 32 °C. It can withstand high to very high temperatures and does not tolerate low temperature below 5 °C. Neem trees can survive even in drought-prone areas like dry coastal area and considered as one of the very few shade-giving trees. The neem trees can survive on even less water and also on poor quality water.

It can grow on wide range of soils up to pH 10 which makes it one of the most versatile and important trees in Indian sub-continent. Due to its multifarious uses, it has been cultivated by

Indian farmers since Vedic period and it has now become part of Indian culture. In India, it occurs throughout the country and can grow well in every agro-climatic zone except in high and cold regions and dam sites. In fact, in India, Neem trees are often found growing scattered in the farmers fields and on the boundaries of fields without affecting the crops.

Table 1: Medicinal values of neem tree

Part	Medicinal uses
Leaf	Eye problem, intestinal worms, anorexia, and skin problem
Bark	Analgesic, alternative and curative fever
Flower	Bile suppression and elimination of intestinal worms
Fruit	Relieves piles, intestinal worms, urinary disorder, epistaxis, eye problem, diabetes, wounds
Twig	Relieves cough, asthma, piles, intestinal worms, spermicidal
Gum	Effective against skin diseases like ring worms, scabies, wounds, ulcers etc.
Oil	Intestinal worms
Seed pulp	Intestinal worms

Farmers practice this system just to meet the local demand for timber, fodder, fuelwood and also for various medicinal properties. Due to its deep tap root system, it does not compete with annual crops for scarce soil moisture. Neem tree can be labelled as wonder tree for its multipurpose uses in real sense. This has been used as a medicinal plant for long time and provides almost all the requirements of rural areas - be the timber, fuelwood, fodder, oil, fertilizers, pest repellent or the ubiquitous 'datun'

Distribution of neem tree

It is grown from the southern tip of Kerala to the Himalayan hills in the tropical to sub-tropical and semi-arid to wet tropical regions and from the sea level to about 700 m elevation. It has been widely cultivated in India and African countries. In India, it occurs throughout the larger parts of the country in the states of Uttar Pradesh, Bihar, West Bengal, Orissa, Delhi, Maharashtra, Gujarat, Andhra Pradesh, Tamil Nadu. The tree is mostly evergreen except in dry localities where it becomes almost leafless for a short period during February - March and the new leaf appears immediately. Flowering spread over January - March in the southern parts of the country and later towards the north. Neem is a light demander and in the young stage it grows very fast. It is hardy but frost susceptible and cannot withstand excessive cold especially during seedling and sapling stage.

Composition of the neem

Neem tree contains nine free fatty acids. The most abundant are 43.1% of oleic acid, 19.4% of palmitic acid, 17.6% of linoleic acid, 16.4% of stearic acid, and 0.3% of arachidic acid; minor fatty acids include 0.6% of odeolidic acid, 0.3% of 3–α-linoleic acid, 0.2% of margaric acid, 0.2% of behenic acid, 0.2% of lignoceric acid, and 0.1% of 1–gadoleic acid. Azadirachtin, a complex tetranortriterpenoid limonoid from the Neem seed, is the main component responsible for both antifeedant and toxic effects in insects. Another limonoid and sulfur-containing compound with repellent, antiseptic, contraceptive, antipyretic, and antiparasitic properties are found elsewhere in the tree, e.g., leaves, flowers, bark, and roots 191.

Neem leaves

Azadirachtin, the main component of neem leaves, flowers and fruits with insecticidal properties that disrupts the growth and development of insects and deters their feeding. It is regarded as a botanical pesticide with superior growth regulating and biocidal effects. medicinal properties of neem leaf have immunomodulatory, anti-inflammatory, antihyperglycemic, antiulcer, antimalarial, antifungal, antibacterial, antiviral, antioxidant, antimutagenic and anticancer properties. The anti-diabetic efficacy of a combination of neem and bitter leaf extracts, and it was concluded that the reduction in blood glucose levels was greater in the groups treated with combined extracts. Neem has a significant health-promoting effect due to its high antioxidant content, in which the study summarised neem's role in disease prevention and treatment by regulating various biological and physiological pathways. The preparation of a quasi-solid-state supercapacitor using activated carbon (AC) electrodes and gel polymer electrolyte (GPE) from neem leaves via chemical activation with zinc chloride as an activating agent, which show that prepared AC is a promising electrode material for supercapacitor applications.

Neem fruit

The neem tree starts fruiting after 3 to 5 years of planting and yield up to 50 kg annually from 10th year onwards. Neem fruit (2 × 1 cm) is nearly oval or round in shape which comprises of thin exocarp, yellowish white mesocarp (bitter sweet pulp) of thickness in the range of 0.3 - 0.5 cm and white hard endocarp containing brown kernel. Engineering properties of neem fruits and seeds for differ based on agroclimatic zones. Neem fruit pulp represents about half the weight of neem fruits which serve as a carbohydrate rich substrate for industrial fermentations. Neem fruits usually matures during the rainy season and contains 40 to 60 % of water which makes it highly perishable and decomposes at a faster rate. So, it is necessary to process neem fruits within 3 to 4 days after harvesting to get good quality of oil from seed kernels. A complete depulping of neem fruits is necessary to obtain good quality of oil within a short period. Traditionally depulping is done manually by hand in which the ripe fruit is rubbed between palms in the bucket of water easily but for dry fruits it is a tedious process which produces poor-quality oil.

Collection and storage of neem fruit

Only fruits at the yellow green colour stage are pricked from the branches. The collected fruits are depulped immediately. Soaking in cold water for a few hours helps in removing pulp. Storing neem seed for 5 months at 40% natural moisture content at 16 degree centigrade is possible. For short storage the seeds are closed in polythene bags and exposed to air once in a week to keep them viable. Long term storage of Neem seeds for more than 10 years is done at 4% moisture content and 20-degree Centigrade temperature. Storage of seed in earthen pot containing wet sand (30% moisture) helps to retain viability up to 60% at the end of 3 months. On an average 5000 seeds weigh one kilogram.

Neem oil

Neem oil is a natural, bioactive plant extract derived primarily from neem seeds, possessing excellent antimicrobial, antioxidant, pesticidal and insecticidal properties, making it an appealing alternative to synthetic chemicals in food preservation, packaging and storage applications. Neem fruit pulp represents about half the weight of neem fruits and it is a promising substrate for methane gas production and it may also serve as a carbohydrate rich substrate for other industrial fermentations.

Neem seed cake

Neem seed cake (NSC) is a by-product of neem oil industry with a potential annual production of about 1 million tonnes. Neem seed cake obtained after oil extraction can be used as an ingredient for livestock feed due to its high protein content of 34 to 38 % and they are also rich in minerals. Neem seed cake can be given as a feed to rabbit in minimal quality without any adverse effect. It can be used as a feed mixture for ruminants as they are facing scare for grains and proteins due to the competition of survival between man and animal in countries like Nigeria. Since it contains bitter triterpenoids, pungent smelling azadirone, nimbin and salanin, it is discouraged and earn low value in feeding live stocks. Several studies and methods are to be developed to reduce bitterness and to eliminate antinutritional factor to make the neem seed cake as a by-product. Neem seed cake and pulp can be used for the biodiesel extraction which needs attention among researchers.

At present, it is largely used as manure cum insecticide and lesser extend used in animal feed industry. It contains the high crude protein, amino acids and minerals profile, and does not spoil on storage or attack by fungi. It was used in the aquatic animal feeds. The inclusion of NSC for animal feed was subjected to a major debate due to the presence of toxic and odour compounds but the proper treatment can solve these problems.

Products made from neem

Neem oil soap

Soap India's supply of neem oil is now used mostly by soap manufacturers. Although much of it goes to small-scale specialty soaps, large-scale producers also use it, mainly because it is cheap. Generally, the crude oil is used to produce coarse laundry soaps. However, more expensive soaps are made by saponifying the crude oil and distilling the resulting fatty acids before adding the lye. The resulting almost colorless and odorless product is suitable for topquality toilet and laundry soap.

Cosmetics

Neem is perceived in India as a beauty aid. Powdered leaves, for example, are a major component of at least one widely used facial cream. Purified neem oil is also used in nail polish and other cosmetics. Lubricants Neem oil is non-drying, and it resists degradation better than most vegetable oils. In rural India it is commonly used to grease cart wheels. It could find many similar lubrication applications in other locations, especially in village settings in the warmer parts of the world where neem can be grown.

Lubricants

Neem oil is non-drying, and it resists degradation better than most vegetable oils. In rural India it is commonly used to grease cart wheels. It could find many similar lubrication applications in other locations, especially in village settings in the warmer parts of the world where neem can be grown.

Applications of neem in agriculture

Agriculture is now a major consumer of neem products such as neem oil, neem cake and neem-based pesticides. Neem manure and pesticide are preferred in organic farming, due to their eco-friendliness and natural source of Phyto - chemicals and nutrients. To reduce nitrogen losses, urea coating with neem products has been prioritised. The Government of India recently permitted fertiliser companies to produce 100 % neem Coated Urea with the goal of increasing farmer income and reducing subsidy bills by up to Rs. 6,500 crores.

According to the World Agro Forestry Centre (WAFC), the market for neem - based pesticides is growing at a rate of 7 to 9 % annually in India and Europe is expected to be the fastest growing market in the future. Neem oil is light to dark brown in colour, bitter, and has a pungent odour. It's mostly made up of triglycerides and a lot of tri-terpenoid chemicals, which give the bitter flavour. Neem oil is a vegetable oil which contains high fatty acid and low terpene content which adds advantage over tea tree oil. Its natural state is hydrophobic. Campesterol, stigmasterol and beta-sitosterol are among the sterols found in neem oil. Because of its environmental benefits and the fact that it is generated from renewable resources, Neem oil has recently become increasingly appealing. It is a renewable, potentially endless energy source with a similar energetic content to diesel fuel. Neem oil has its application in the field of cosmetics, medicines, soap making and mosquito repellent. nee m vermicomposting of neem using high - rate reactors operated at earthworm densities of 62.5 and 75 animals per litre of reactor volume which revealed that the vermicompost had a positive effect. neem oil as a potential feedstock for biodiesel production and suggested the optimization of neem biodiesel production followed by evaluation of engine performance and emission characteristics.

Neem extracts contain a natural chemical called azadirachtin. The substance is found in all parts of the tree. The leaves are used effectively, though the chemical is much more concentrated in the fruit, especially in the seeds. Neem extracts do not usually kill insect pests immediately. They change the feeding or life cycle of the insect until it is no longer able to live or have young. This might mean that the neem extract takes a long time to work if the pest attack is severe. Other insects will avoid a plant treated with neem extracts. When neem products are exposed to light, they begin to lose their ability to control pests. For this reason, the commercial neem-based insecticide, Margosan-O, that is sold in the USA, contains a sunscreen. Neem based pesticides are suitable for use in developing countries because the useful chemicals can be easily removed from the neem without the use of expensive and complicated equipment.

Neem as fertilizer

The material left after oil is squeezed out from seeds and is popularly known as the neem seed cake; it acts as a bio fertilizer and helps in providing the required nutrients to plants. It is widely used to ensure a high yield of crops. Neem is used as a fertilizer both for food crops and cash crops, particularly rice and sugarcane crop. It contains more nitrogen, phosphorus, potassium, calcium, and magnesium than farmyard manure or sewage sludge. Surprisingly, neem cake sometimes seems to make soil more fertile than calculations predict. This is apparently due to an ingredient that blocks soil bacteria from converting nitrogenous compounds into (useless) nitrogen gas. When mixed with urea, for example, neem cake cuts down on the amount of urea converted to nitrogen gas in the soil. So far, this finding, which might prove to be a major breakthrough, has not been pursued beyond the laboratory. If it proves real in everyday practice, it might boost the effectiveness of fertilizers everywhere— restoring to the soil that part of their power now lost by bacterial action. Neem seed cake performs the dual function of both fertilizer and pesticide, acts as a soil enricher, reduces the growth of soil pest and bacteria, provides macro nutrients essential for all plant growth, helps to increase the yield of plants in the long run, bio degradable and eco-friendly and excellent soil conditioner.

Neem as manure

Manure is any animal or plant material used to fertilize land especially animal excreta for improving the soil fertility and thus promoting plant growth. Neem manure is gaining popularity because it is environmentally friendly and also the compounds found in it help to increase the nitrogen and phosphorous content in the soil. It is rich in sulphur, potassium, calcium, nitrogen, etc. Neem cake is used to manufacture high quality organic or natural manure, which does not have any aftermaths on plants, soil and other living organisms. It can be obtained by using high technology extraction methods like cold pressing or other solvent extraction. It can be used directly by mixing with the soil or it can be blended with urea and other organic manure like farm yard manure and sea weed for best results.

Neem as urea coating agent

Neem and its parts are being used to manufacture urea coating agent to improve and maintain the fertility of soil. The fertility of the soil can be measured by the amount of Nitrogen, Potassium and Phosphorous it has; there are certain bacteria found in soil, which denitrify it. Use of neem urea coating agent helps to retard the activity and growth of the bacteria responsible for 194 denitrifications. It prevents the loss of urea in the soil. It can also be used to control a large number of pests such as caterpillars, beetles, leafhoppers, borer, mites etc. Urea coating is generally available either in liquid form or powdered form. Properties of Neem Urea Coating are Anti feedant, anti-fertility and pest growth regulator.

Neem as soil conditioner

Neem seed granules or powdered seeds are used to manufacture the soil conditioner. It can be applied during sowing of plants or can be sprinkled and raked into the soil. The process of sprinkling should be followed by proper irrigation so that the product reaches the roots. It is a natural soil conditioner that helps improve the quality of soil, thereby enhancing the growth of plants and fruits. Organic soil conditioner is gaining popularity in agricultural industry, not only in Asian countries like India but also in western counterparts such as USA, UK and Australia. Neem is a natural soil conditioner that helps improve the quality of soil, thereby enhancing the growth of plants and fruits. It not only helps the plants grow, but also prevents them from being destroyed by certain pests and insects. Organic soil conditioner is gaining popularity in agricultural industry. Because they are organic, they have no harmful effects and are cheaper than the other soil conditioners. This natural soil conditioner is also multi-functional and, in the subtropical regions. Neem soil conditioner application in plantation crops is known to be a soil enhancer that helps to increase its fertility.

Neem as pesticide

Neem pesticides play a vital role in pest management and hence have been widely used in agriculture. There has been an evident shift all over the world from synthetic pesticides to non-synthetic ones; this is largely because of the wide spread awareness of the side effects of these synthetic pesticides not only on plants and soil but also on other living organisms. This is a great opportunity for neem pesticides manufacturers to cash in on the growing popularity of natural or herbal pesticides. Neem pesticides are being manufactured and exported to various countries as a lot of research has been conducted to test the safety and efficacy of neem for use as a pesticide. Azadirachtin is the main ingredient used to manufacture bio pesticides. Neem oil and seed extracts are known to possess germicidal and anti-bacterial properties which are useful to protect the plants from different kinds of pests. One of the most important advantages of neem-based pesticides and neem insecticides is that they do not leave any residue on the plants.

Neem as fumigant

Neem tree has been used against household, storage pests and crop pests. Neem pest fumigant is available in gaseous state and is used as a pesticide and disinfectant. It is being used by a large number of countries on a commercial basis by farmers and agriculturists. This 100% natural product is being exported as it is nontoxic and does not affect the environment. It assumes more importance in developing countries where millions of deaths are reported every year due to the accidental intake of synthetic pest fumigants. This natural fumigant not only kills pests but also affects them negatively by acting as feeding and oviposition deterrence, mating disruption, inhibition of growth etc. According to studies undertaken, neem fumigant helps to protect stored rice grains from pests. One of the major benefits of this organic fumigant is that pests do not develop resistance to it. With the increasing trend of using bio fertilizers, insecticides and pesticides, neem is being increasingly cultivated and grown all over the world to get active ingredient-azadirachtin, responsible for stopping the growth cycle of insects and pests, fungi etc. Neem is also assuming a lot of importance in crop management. Considering the fact that neem is not only a cheaper, naturally occurring product and an effective method to control pests and insects, but also has no side effects on plants or other living beings, it is not a wonder that researches are being carried to try neem and its products for large scale production of natural pesticides and insecticides. This is a good opportunity for manufacturers and exporters to produce quality bio agricultural products. Neem oil and seed extracts are known to possess germicidal and anti-bacterial properties which are useful to protect the plants from different kinds of pests. This natural product does not leave any residue on plants.

Applications of neem oil in food industry

The biopolymer properties of neem leaf extract (NLE) and their tensile properties for the food packaging applications and developed a biopolymer-based plastic which was green in colour and was observed no fungal or bacterial growth on the bio polymeric film which indicated its medicinal and aseptic properties. Neem essential oil and nano zinc oxide into the chitosan polymer to enhance the properties of the bio nanocomposite film for carrot packaging and found that 0.5% nano zinc oxide and neem oil incorporated composite film showed improved tensile strength, elongation, film thickness, antibacterial activity. The neem oil and its nano emulsion have various applications like food packaging material. Neem oil and its nano emulsion has excellent antimicrobial, antioxidant, pesticidal and insecticidal properties which has been used in chitosan, starch, or pectin based active packaging and coatings. Neem oil used in active agar (AG) bilayer film with bioactive capability and electrochemical property for improving the postharvest quality of the banana by incorporating neem essential oil (NEO) and TiO_2 into the AG lower layer and upper layer which exhibited the optimal preservations on banana fruits.

Neem oil as natural preservative

Plant-derived extracts (PDEs) are a source of biologically-active substances having antimicrobial properties. neem oil (NO) as a preservative of fresh retail meat. The antibacterial activity of NO against Carnobacterium maltaromaticum, Brochothrix thermosphacta, Escherichia coli, Pseudomonas fluorescens, Lactobacillus curvatus and L. sakei. The post-antibiotic age will be announced when no medicinal drug will be able to successfully fight the multiresistance of microorganisms. The need of novel antibiotics is not limited to medical drugs, but other fields appear very important and crucial for our future. The exploration of plant-derived antimicrobials should be an innovative way to find alternative substances to current antibiotics.

Plants and their agro-industrial waste and by-products constituents are sources of biologically-active substances compared to the current antibiotics. They represent innovative opportunities to control microorganisms in food as alternative to synthetic preservatives. Spoilage bacteria that negatively influence meat products, causing sour off-flavors, discoloration, gas production, slime production and a decrease in pH, belong to Gram-positive, Gram-negative, anaerobic and facultative genera. These effects have been attributed, among others, to the action of extracellular compounds, such as lipases and proteases, produced by dominant spoilage microorganisms.

Brochothrix thermosphacta is an economically important psychrotrophic, facultative anaerobic, meat-spoilage microorganism, because it is commonly present in refrigerated meat and meat products packaged in different ways. It produces malodorous metabolic end products, such as acetoin and acetic, isobutyric and isovaleric acids, which make meat unpalatable. This bacterium can display lipolytic activity also at refrigeration temperature. The responsible spoilage metabolites of Carnobacterium spp. are not structurally well characterized, but branched alcohols and aldehydes play a partial role. Escherichia coli presence is considered an indicator of the quality of packed meat. A high presence of E. coli (higher than 100 per g) on stored meat could indicate temperature abuse, because it does not grow below 7 °C. E. coli presence may also indicate a food safety issue. Its contamination does not cause an odour.

Pseudomonas species live in soil, water, on the surface of animal skin, on plants, on many man-made structures and clinical setting. The bacteria in this genus all have strong, durable cell walls. They can utilize diverse compounds, including various hydrocarbons, as carbon and energy sources. This ability is linked to the production of biosurfactants that allow Pseudomonas spp. to utilize and degrade fat associated with meat. The lactic acid bacteria (LAB) are implicated in bloating spoilage of vacuum-packed and refrigerated meat products. Leuconostoc spp. and Lactobacillus spp. genera, involving psychrotrophic lactic acid, cause spoilage of cold-stored, modified-atmosphere-packaged (MAP) and nutrient-rich foods.

Food packaging provides an easier distribution and protects food from environmental conditions, such as light, oxygen, moisture, microorganisms, mechanical injury and dust. Active packaging acts by preserving the condition of the packed food and leading to an increase in shelf life and improvement in safety and sensory properties. Foods 2015, 4 5 In addition, the application of such packaging methods on the product surface before packaging can create an environment that may delay or even prevent the growth of undesirable organisms.

Medicinal uses of neem tree

Medicinal value of neem oil

Neem oil has excellent antibacterial, antifungal, antioxidant, insecticidal, pesticidal and plasticizer properties and finds its applications in food preservation, packaging and storage. Bioactive phytochemicals such as azadirachtin, salannin, nimbidin, gedunin, nimbin, isomargolonone, margolone, nimbolide, margolone etc present in neem oil. Neem oil is attractive choice for active food packaging applications due to its antibacterial and antioxidant characteristics with maximum tensile strength, elongation and transparency. Neem oil mixed with 2 % coconut oil can be applied to exposed body parts of human volunteers. Neem oil provided complete protection from all anopheline species bites for 12 h. The use of neem oil was safe and can be used to protect against malaria in malaria - endemic countries. The efficacy of NIM - 76, a spermicidal fraction of neem oil, against certain bacteria, fungi, and the Polio virus when compared to whole neem oil, which showed that NIM - 76 had a potent broad spectrum anti-microbial activity.

Antimicrobial and anti parasitic effect of neem tree

Antibacterial effect Neem possesses a wide spectrum of antibacterial action against Gram-negative and Gram-positive microorganisms. The antibacterial activity of neem extracts against 21 strains of foodborne pathogens was evaluated and result of the study suggested that it possess compounds containing antibacterial properties that can potentially be useful to control bacteria and spoilage organisms. Another experiment was made to evaluate the antibacterial activity of the extracts of A. indica on bacteria isolated from adult mouth and results revealed that bark and leaf extracts showed antibacterial activity against all the test bacteria used. Water extracts of neem twigs inhibits growth of dental caries organisms *Streptococcus mutans, S. salivarius, S. mitis,* and *S. sanguis*. Neem has suppressed several species of pathogenic bacteria, including: Staphylococcus aureus, a common source of food poisoning and nonperforming. The susceptibility of the microorganisms to the extracts of neem leaves was compared with certain specific antibiotics. Its leaves possessed good anti-bacterial activity, confirming the great potential of bioactive compounds and is useful for rationalizing the use of this plant in primary health care. The methanol extract of A. indica exhibited pronounced activity against Bacillus subtilis.

Antifungal effects

Nimbidin, Nimbin, Nimbidol and Neem oil are very effective against fungi like Tinea rubrum ring worm fungus, Trichophyton interdigitale, Coccidioides immitis and species of Trichophyton at very low concentration. High antimycotic activity with extracts of different parts of neem has already been reported. Extracts of leaf, oil and seed kernels are effective against certain human fungi; due to this property is given great importance in the field of science. Neem leaf extract has antifungal activity against three fungal species: Aspergillus flavus, Alternaria solani and Cladosporium. Neem oil has been the cure for many fungal diseases caused by the above fungi which has been a lifesaver. The ethanolic extract of neem leaves is more effective against Rhizopus compared to aqueous leaf extract. Aqueous and ethanolic extract of neem leaves were found effective against Candida albicans by which these organism shows sensitivity at the concentration of 15% and 7.5% on aqueous extract. Neem oil is used to prevent aflatoxin which is produced due to contamination of the poultry feed by fungus and the neem leave extract antagonises the production of Patulin caused by Penicillium expansium.

Antiviral effect

Neem leaves are found to be effective against Dengue virus type -2 in which it halts the replication of the virus itself in an invitro environment and in the laboratory animals. The aqueous extract of its bark was found to be effective against Herpes simplex virus type 1 by blocking its entry into natural target cell. Even though it does not cure it shows the ability to prevent smallpox, chickenpox and fowl pox. In HIV/AIDS patients, a 12-week oral administration of acetone water neem leaf extract (IRAB) had a significant influence in vivo on CD4 cells (which HIV reduces) without any adverse effects in the patients. It may be applied topically to appropriate parts of the body during an outbreak or just prior, when stress is high and we begin to get that ‘feeling’ that often occurs just before an outbreak. To speed relief, one may also take the oral supplements, such as neem leaf capsules

Extraction of neem oil

Many methods have been used for extraction of neem oil, the most common among which are mechanical pressing, solvent extraction, and supercritical fluid extraction. In the mechanical extraction method, neem oil is extracted by mechanical crushing of the seed at controlled or cold temperature. Mechanical extraction technique is most commonly used because it is convenient, solvent-free, economical, and about 82% of neem oil is extracted using this method. Although, the oil extracted by this method is of poor quality and low market value due to low azadirachtin content, presence of significant amounts of water and metal that makes the oil turbid and impure. Neem oil consists of more than 300 biologically active compounds, of which the major constituents are triterpenes known as limonoids (sal- annin, nimbin, nimbinin, meliantriol, azadirachtin, quercetin, etc.), antioxidants, fatty acids, and triglycerides, etc.. The color of neem oil varies from yellow brownish, dark brown, golden yellow, reddish brown, greenish brown to bright red. Neem kernel oil is also a major source of fatty acid, and mainly composed of oleic acid (44.98%), stearic acid (21.26%), palmitic acid (16.78%) and linoleic acid (14.18%). Neem oil contains limonoids, calcium, etc.

Traditional method of neem seed oil extraction

The traditional method of neem seed oil extraction permits the extraction of about 17.63 % from the kernel, which is inefficient and time consuming. The traditional method of neem seed oil involves the following steps:

Collection of fruits/seeds:

Fruits and dry seeds are collected from neem trees.

Cleaning, drying and sorting of seeds

The ripe fruits and seeds collected are cleaned by washing in ordinary water and rubbing with the palms to remove the skin of the fruits. The cleaned seeds are then dried by spreading in the sun to reduce the moisture content of the seeds. This is followed by removing unwanted materials such as stones and dirt by hand picking. Shelling of seed and winnowing. Shelling of seeds to obtain clean kernel is carried out by the use of grinding stones winnowing is achieved by holding baskets filled with mixture of seeds and shells at arm length and gradually emptying them. If there is strong wind, the pieces of shell will be blown away, if not, the operation is repeated many times.

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THE QUANTITATIVE IMPERATIVE: MATHEMATICS AND STATISTICS IN GENETIC PRINCIPLES AND THEORY

C Rama Raju*[1], Bolla Saidi Reddy[2], T. Dinaker Chinna[3] and T. Uma Kiran[4]

1 Government Degree College, Badangpet, Dist. Ranga Reddy,
Osmania University, Telangana, India.
2 Government Arts & Science College (A) Kodad, Dist. Suryapet,
Mahatma Gandhi University, Telangana, India.
3 Government Arts & Science College (A) Kamareddy, Dist. Kamareddy,
Telangana University, Telangana, India.
4 Girraj Government College (A), Nizamabad. Dist. Nizamabad,
Telangana University, Telangana, India.
*Corresponding author E-mail: botanybdpt@gmail.com

Abstract:

The integration of mathematics and statistics into genetics has transformed the field from descriptive observations to predictive, theory-driven science. Quantitative models underpin Mendelian inheritance, population genetics, and modern molecular approaches, facilitating precise predictions about allele distributions, genetic variation, and evolutionary dynamics. This chapter explores classical principles, including probability theory, Hardy–Weinberg equilibrium, and heritability, alongside modern statistical and computational methods such as quantitative trait loci (QTL) mapping, genome-wide association studies (GWAS), and predictive genomic modeling. Emphasis is placed on the synergistic role of mathematics and statistics in linking empirical observations to theoretical insights, demonstrating that quantitative reasoning is central to understanding genetic principles across scales.

Keywords: Genetic Theory, Quantitative Genetics, Population Genetics, Statistical Genomics, Computational Modeling.

1. Introduction:

Genetics has evolved from Mendel's foundational experiments with pea plants to a highly quantitative discipline in the era of genomics. The study of inheritance relies on mathematical structures and statistical reasoning to describe, predict, and explain patterns observed in populations. Early geneticists recognized the power of numerical approaches, but the integration of probability, statistical inference, and computational modeling has accelerated our understanding of complex traits and evolutionary processes.

Mathematics allows for precise expression of Mendelian ratios, population allele frequencies, and dynamics of gene flow and selection. Statistics bridges the gap between theoretical predictions and empirical data, enabling estimation of heritability, identification of genetic loci underlying complex traits, and detection of genotype–phenotype associations. This chapter aims to present a balanced integration of classical and modern quantitative approaches, emphasizing how mathematics and statistics are indispensable to genetic theory.

2. Mathematics in mendelian and population genetics

Mendelian genetics provides the first formal framework for quantitative reasoning in inheritance. The probability of inheriting alleles follows binomial distributions, forming the basis of Punnett squares and genotype ratios. For a monohybrid cross, the probability (P) of obtaining a particular genotype can be expressed as:

$$[\ P(AA) = p^2,\ P(Aa) = 2pq,\ P(aa) = q^2\ ]$$

where (p) and (q) are the allele frequencies of (A) and (a), respectively.

Table 1: Monohybrid Cross Genotype Probabilities

Genotype	**Probability**
AA	p^2
Aa	$2pq$
aa	q^2

The Hardy–Weinberg equilibrium formalizes the relationship between allele and genotype frequencies in idealized populations:

$$[p^2 + 2pq + q^2 = 1\ ]$$

Deviation from equilibrium indicates evolutionary forces such as selection, mutation, or drift. Population genetics uses these mathematical formulations to predict changes in allele frequencies across generations.

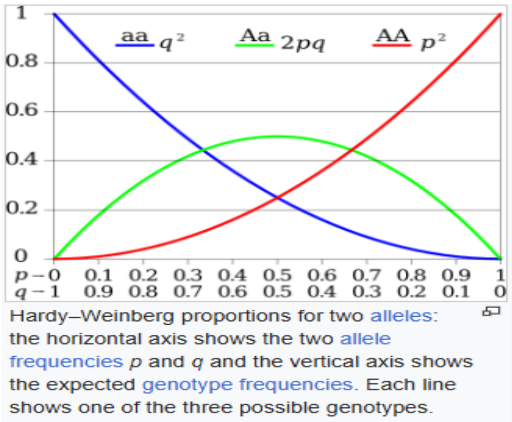

Figure 1: Diagram showing allele frequency distribution and Hardy–Weinberg equilibrium (Source: Wikipedia)

3. Statistical foundations in quantitative genetics

Quantitative traits, influenced by multiple genes and environmental factors, require statistical approaches for analysis. Variance components partition phenotypic variance ((V_P)) into genetic ((V_G)) and environmental ((V_E)) contributions:

$$[V_P = V_G + V_E\ ]$$

Heritability ((h^2)) quantifies the proportion of phenotypic variance attributable to genetics:

$$[h^2 = \frac{V_G}{V_P}]$$

Table 2: Heritability Classification

Trait Type	Heritability Estimate
Low	<0.2
Moderate	0.2–0.5
High	0.5

Regression and correlation analyses are applied to assess genetic relationships among traits. These foundational statistical techniques enable breeders and geneticists to make predictions and select for desirable phenotypes efficiently.

4. Probability models and genetic variation

Probability theory underpins models of genetic variation, including the effects of genetic drift, selection, mutation, and migration. The Wright-Fisher model and coalescent theory employ stochastic processes to describe allele frequency dynamics in finite populations. For example, the probability of allele fixation under genetic drift depends on initial allele frequency (p_0) and population size (N):

$$[\ \mathrm{P}\{\mathrm{fix}\} = p_0\ ]$$

Graphical simulations illustrate how small populations experience rapid fluctuation in allele frequencies compared to large populations. This applies regardless of the population size (N), though fixation occurs more rapidly and with greater fluctuations in small populations

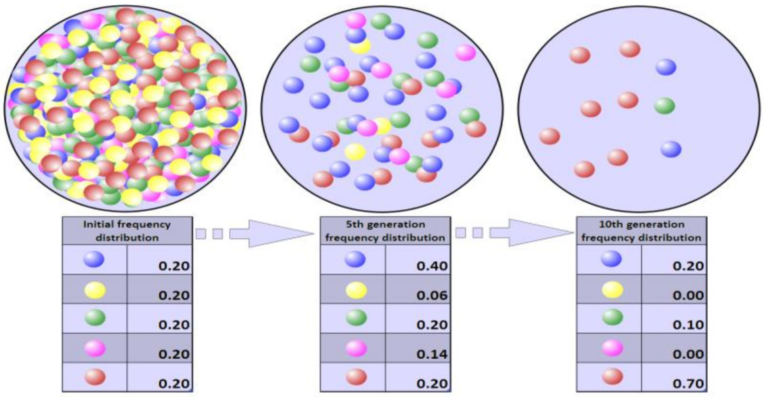

Figure 2: Simulation of allele frequency changes under genetic drift in populations of different sizes. (Wikimedia commons)

5. Applications in molecular and genomic genetics

Modern genetics leverages statistical frameworks to analyze high-dimensional molecular data. Quantitative Trait Loci (QTL) mapping identifies genomic regions associated with phenotypic variation. The association between genotype and phenotype is modeled statistically, often using linear models:

QTL mapping and its extension, GWAS, typically rely on linear models to test for associations between genotype and phenotype.

The linear model is expressed as $\boldsymbol{y} = \boldsymbol{\alpha} + \boldsymbol{X\eta} + \boldsymbol{\epsilon}$

$\boldsymbol{y}$ is the vector of phenotype measurement (e.g., height for each individual).

$\boldsymbol{\alpha}$ s the intercept, which can represent the population mean of the trait.

$\boldsymbol{X}$ is the genotype matrix, with each column representing a genetic marker and each row representing an individual.

$\boldsymbol{\eta}$ is the vector of effect sizes for each genetic marker.

$\boldsymbol{\epsilon}$ is the vector of residual error, accounting for environmental effects and other unmeasured variables.

GWAS: This method extends the principle of QTL mapping to an entire genome, analyzing hundreds of thousands or even millions of genetic markers (typically single nucleotide polymorphisms, or SNPs). Because of the large number of tests, GWAS requires stringent statistical corrections for multiple testing to identify true associations.

6. Computational and Predictive Modeling in Modern Genetics

Advances in bioinformatics allow simulation and prediction of genetic outcomes under various evolutionary scenarios. Machine learning and Bayesian modeling enable genotype-to-phenotype predictions with large datasets, integrating environmental variables and epistatic interactions. Computational approaches also simulate breeding outcomes, evolutionary dynamics, and population responses to selection.

Table 3: Computational Approaches in Quantitative Genetics

Method	**Application**
Linear regression	Trait prediction
Bayesian modeling	Estimating effect sizes, heritability
Machine learning	Genomic selection, phenotype prediction
Monte Carlo simulations	Evolutionary scenario modeling

Conclusion:

Mathematics and statistics are the backbone of modern genetics. Classical probability models and population genetics principles provide foundational insights, while molecular and computational approaches extend these frameworks to high-dimensional genomic data. Integrating quantitative reasoning across scales enables prediction, inference, and understanding of complex genetic phenomena. The "quantitative imperative" is clear: a deep understanding of genetic principles requires rigorous mathematical and statistical literacy.

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SPIRULINA FOR PROTEIN-RICH SNACK BARS: A FUNCTIONAL FOOD APPROACH

Kavita Mane* and Satyam Doiphode

School of Food Technology,

MIT Art, Design and Technology University, Pune

*Corresponding author E-mail: kavita83.more@gmail.com

Abstract:

The increased awareness towards health benefit-oriented functional food and eco-friendly eating habits led transformation in the food choices of consumers. A unicellular microphyte (Spirulina) is a prominent resource of vitamins, minerals, antioxidants, and essential fatty acids, that makes it an ideal ingredient for functional foods. The utilization of this superfood as a nutrient-dense microalga recognized for profusion of protein and essential amino acids in snack bar production is explored in the present chapter. Snack bars infused with spirulina offer a promising way to meet the increasing desire of consumer for sustainable, plant-based, and healthy food options.

The formulation of snack bars comprises combination of spirulina powder with additional protein rich ingredients like Bengal gram, soybean, pea nuts, and whole grains to ensure a balanced nutritional profile. Vigilant ingredient selection is crucial to mask the distinct earthy flavour and green colour of spirulina. Because of high protein and antioxidant content, these bars provide several health benefits like improving immune health, muscle support, and prolonged energy. This chapter explores opportunities for enhancing nutritional value of snack bar to meet market demand and improve sensory appeal for consumer satisfaction.

1. Introduction:

Meals with lower nutrients like protein and minerals are contributing to increased level of malnutrition that adversely affects development in children. It is now a days a global need that all people should get access to a nutritious and healthy diet which is affordable to all economic groups while being sustainable. The snack food sector has undertaken substantial transformation to fulfil the need for convenient and wholesome meal options in the era of budding health-conscious consumers. Protein-rich snack bars are increasingly preferred by consumers looking for convenience and health advantages. These bars have become popular among athletes, health enthusiasts, and individuals keen to maintain a balanced diet as it provides a balanced energy source that offers them with an ideal on-the-go snacks for their hectic lifestyles. In this context, spirulina, a blue-green microalga with extensive nutrients and bio-compound profile is recognized across the globe to improve the health of people. Spirulina is a powerhouse of nutrients comprising 60 to 70 % protein with necessary amino acids, and micronutrients like vitamins and minerals. It is also a source of powerful antioxidants and essential fatty acids, making it a comprehensive supplement for enhancing overall health. Its composition providing antioxidant, antimicrobial, and anticarcinogenic properties aids in treating certain diseases by strengthening the immune health and reducing inflammation. The digestibility and bioavailability of spirulina make it a preferred protein source for various demographics, including vegetarians and individuals with dietary restrictions.

Snack bars are emerged out as one of the ideal options to enhance the nutritional profile by adding spirulina. As a safe food deprived of any toxicity, spirulina is already permitted by FDA (Food and Drug Administration) and certified as GRAS (Generally Recognized as Safe). Bakery products like cookies and extruded snack products are already enriched with spirulina to grab its health benefits. Incorporation of spirulina into snack bars not only increases protein content but also supplements them with micronutrients like vitamins and minerals supporting many body functions. Moreover, spirulina production requires less land and water than traditional protein sources, projecting its alignment with the growing consumer preference for eco-friendly food choices.

The formulation, processing, and potential market opportunities for protein-rich spirulina snack bars are explored in present chapter. By examining the nutritional and health benefits, challenges, and consumer trends, the chapter aims to highlight the significance of spirulina as a valuable constituent in the functional food development, providing an innovative snack option to cater health-conscious consumers seeking for nutritious and convenient alternatives.

2. Spirulina as a protein rich ingredient for product development

A unicellular microphyte, *Arthrospira platensis* (often known as Spirulina), can thrive in brackish, salt, and fresh water. Spirulina grows significantly at an extremely alkaline pH range of 10–12. It is a naturally occurring protein source, which has five times more proteins than meat (Capelli and Cysewski, 2010). Spirulina contains up to 70% protein, which includes amino acids, fatty acids, polysaccharides, vitamin B12, β-carotene, and iron (Mohan *et al.*, 2014). Anticancer, antioxidant, antiviral, immunomodulatory, and having a good impact on malnourishment, diabetes, obesity, anemia, and inflammatory allergic reactions are just a few of the health advantages of spirulina. Spirulina got an approval from FDA as safe and now most of the countries including USA, Japan, France, and India have all accepted spirulina for use in food products as a means of treating malnutrition. The global population have experienced an increased protein deficit in 1950, which compelled all scientists and researchers to look for novel alternative protein sources. Algal biomass appears to be a reasonable material at that point for this goal (Soheili and Darani, 2011). Over a thousand metric tons of spirulina platensis are produced annually worldwide. Various organizations highlight the nutritional and medicinal benefits of spirulina, which is sold under various brand names in a powder or tablet form and used for purposes like fitness, bodybuilding, and weight loss (Khan *et al.*, 2005).

3. Nutritional profile of spirulina

Spirulina has an impressive amino acid profile with helpful nutrients like bioactive compounds, fatty acids, vitamins (B1, B2, B3, B6, B9, B12, C, D and E), and minerals (Kumari *et al.*, 2011). The mineral content profile (K, Ca, Cr, Cu, Fe, Mg, Mn, P, Se, Na, Zn) of spirulina is comparable with milk (Kumari *et al.*, 2011). It is a source of diverse carotenoids (Chlorophyll A, xanthophyll, β- carotene, echinenone, myxoxanthophyll, zeaxanthin, canthaxanthin, diatoxanthin, 3-hydroxyechinenone, beta-cryptoxanthin, oscillaxanthin, phycobiliproteins, C-phycocyanin, and allophycocyanin) and enzymes. Spirulina protein reflected equivalent digestive properties as that of pure casein (Hoseini *et al.*, 2013). The dry form of spirulina has 60% protein with all necessary amino acids (Kumar *et al.*, 2015). Spirulina is the only food containing phycocyanin C which is the most important pigment and considered as precursor of chlorophyll and hemoglobin. The presence of vitamin B12 in spirulina is higher than the beef liver and β-carotene is 10 times more concentrated than in carrot. Spirulina contains 1.8-fold higher calcium than that of whole milk and 10-fold higher iron than spinach. It contains up to 70% proteins, 25% polysaccharides, 6% lipids, 13% nucleic acids and 4.8% minerals (Kumar *et al.*, 2018). The nucleic acid in spirulina is less than 5% which makes it desirable as food. It has good quantity of methionine, cysteine, and lysine though comparatively lesser to animal protein sources (meat, egg, and milk), but relatively more than plant protein sources. It contains 36% of polyunsaturated fatty acids (γ-linolenic acid, linoleic acid, stearidonic acid, eicosapentaenoic acid, docosahexaenoic acid, and arachidonic acid) and up to 2.0% of total lipids (Jung *et al.*, 2019).

4. Health benefits of spirulina

Spirulina strengthens the immune system and improves its working by regulating the functionaries of its vital cells and organs to while dealing with the pressure of environmental toxins and communicable agents (Khan *et al.*, 2005). Spirulina as an amusing natural source of β-carotene and phycocyanin projected its efficacy in prevention of cancer, ulcer, piles, and other non-communicable diseases. Substantial research carried out on clinical studies supports the reducing the rate of cancer in animals and enhancement in the recovery of oral cancer patients because of β-carotene and phycocyanin content in spirulina. It also reduces the level of total cholesterol, triglycerides, and LDL. Spirulina helps maintain a healthy population of good bacteria like *Lactobacillus* and *Bifidus* and hence reduces the potential problems caused by pathogens like *E. coli and Candida albicans*. Spirulina enhances the absorption of nutrients from food and lowers blood glucose level and supports reduction in the glycosylated hemoglobin (Kulshreshtha *et al.*, 2008). Spirulina has shown effectiveness in treating diabetes mellitus type II and preventing the risk of cardiovascular risk factors as it has a complimentary effect on glycemic control and lipid patterns (Tang and Suter, 2011). Spirulina contains predominant xanthophyll called zeaxanthin that helps in reducing the chances of cataracts and age-linked macular erosion. It contains bioactive compounds like carotene, xanthophyll phytopigments and phycocyanin posing antioxidant properties (Hoseini *et al.*, 2013).

Spirulina contains calcium spirulan, a novel sulfated polysaccharide which is responsible for antiviral activity to oppose variety of encased infections such as herpes simplex virus type-I, measles virus, human immunodeficiency virus-I and influenza virus. About 50% and 23% reduction in viral load were reported for spirulina extracts. Spirulina showed protective role in allergic reactions like asthma, atopic dermatitis, and allergic rhinitis and ischemic brain damage (Nuhu, 2013). Spirulina as a source of natural antioxidants (β-carotene and tocopherol) protects the body from oxidative stress that becomes reason of noncommunicable diseases like diabetes, atherosclerosis, arthritis, cancer etc. Spirulina increases red cell production and its function. Also, within the consumption of spirulina the mean corpuscular haemoglobin increases steadily. People suffering from anaemia can recover quickly by supplementation of spirulina. Spirulina lowers body weight and blood cholesterol levels in humans by 4.5%. Additionally, liver damage, inflammatory response, cell degeneration, and anaphylactic reaction are all decreased by spirulina. Its high iron, vitamin B12, and vitamin A content guards against pernicious anaemia, hypoferric anaemia, and eye disorders. Tumour necrosis factor is induced in macrophages by spirulina, which is an indication of a prospective approach towards tumour eradication (Saranraj and Sivasakthi, 2014). Palaniswamy and Veluchamy (2018) reported that phycocyanin is a pigment found in spirulina which has anticancer properties that helps in preventing cancer. The cohesion of antioxidants and immune monitoring properties associated with spirulina have positive effects on cancer causing tumor destruction. The absence of cellulose in spirulina results in easy digestion and absorption. So, its consumption has beneficial effect against kwashiorkor, by strengthening the intestine's functional capability. Spirulina offers anti-bacterial effects on pathogenic bacteria while reducing virus multiplication at larger level and neutralizing or detoxifying the harmful effects of heavy metals projecting anti-cancer activity. (Jung *et al.*, 2019)

5. Spirulina enriched food products

The pasta developed by utilizing spirulina not only gives higher protein content but projects better techno-economic feasibility as compared to pasta devoid of spirulina (Lemes *et al.*, 2012). The microbiological quality followed the regulatory aspects with satisfactory sensory quality as well as high purchase intention. Spirulina powder has intrinsic usage in milk industry to produce value added milk products (Malik *et al.*, 2013). Moreover, it can be used to substitute stabilizers for ice cream production without disturbing the sensorial profile of ice cream and making it more nutritive. Spirulina incorporated food for children of age 1-3 years found to be microbiology safe with acceptable sensory characteristics (Sharoba, 2014). Spirulina is safe for little ones and is recommended by the World Health Organization (WHO). The protein, carbohydrate, calcium, magnesium, and iron content of spirulina fortified bread are more than the standard bread (Burcu *et al.*, 2016). Addition of spirulina inhibits the growth of moulds in breads. Thus, spirulina does not have negative effects on shelf life however it improved the nutritional value. The enrichment of spirulina in crackers and instant noodles not only increases protein content, vitamins, and essential amino acid level but provides improved textural and sensory characteristics (Amira *et al.*, 2017).

6. Preparation of protein-rich spirulina snack bars

Spirulina enriched nutrition bar contains higher protein content than standard bar (Kumar *et al.*, 2018). Along with spirulina, Bengal gram, groundnuts, and cornflakes also plays an important role in increasing protein content of nutrition bar. Addition of spirulina decreases carbohydrate content and increased minerals content significantly.

Spirulina (2-6 %) infused protein rich snack bars can be formulated using protein rich sources like bengal gram (15 %), peanuts (15 %), oats (8-12 %), puffed rice (2 %), soy isolate (4 %), and other ingredients like desiccated coconut (4 %), corn syrup (25 %), honey (20 %), and flavors like cardamum powder (1 %). The blending of all dry ingredients in binding syrup (corn syrup + honey) with continuous stirring, sheeting, and cutting results in protein rich snack bars. The bars can be wrapped in butter paper and packed in polypropylene (200-gauge) after cooling at room temperature.

7. Market trends and consumer demand

The market for protein bars has grown rapidly, due to the increased demand for on-the-go snacks that offer a combination of taste, nutrition, and convenience. Consumers prefer healthier snack options selecting the products that support their wellness and fitness goals. The increasing awareness of plant-based diets and demand for vegan food have elevated the market opportunities for protein substitutes like spirulina-infused products. High protein content and sustainable cultivation, makes spirulina as a desirable ingredient for eco-conscious consumers looking for plant-based protein sources.

8. Shelf life and storage

Spirulina infused protein rich snack bars have good shelf life from 3 to 6 months, when kept in sealed and moisture-proof packaging. However, oxidative rancidity might happen due to presence of inherent oils in other ingredients like nuts and seeds. Natural preservatives like rosemary extract or antioxidants like vitamin E can be used to enhance the shelf life of bars.

9. Challenges in product development

Despite of spirulina's great nutritional value, its addition to snack bars poses challenges in maintaining anticipated sensory profile. Desirable texture, attractive colour and appearance, balanced profile of taste and flavour are crucial to produce consumer acceptable bars. It is crucial to have the ideal texture by striking a balance between chewiness and crispness of bars. Appropriate moisture levels and the usage of binders play important role in maintaining the right texture. A rich green colour of spirulina could affect consumer acceptance. Hence, visual appeal of spirulina-based food product can be enhanced by careful formulation. Also, appropriate ingredient formulation is required to mask the distinctive earthy taste of spirulina.

Future opportunities and conclusion

Spirulina-based snack bars have a lot of potential because of the increased demand for plant-based and high-protein diets. These bars can cater to athletes, health-conscious people and individuals looking for sustainable dietary options. Spirulina is expected to be used increasingly in conventional food products as people are aware of its benefits, making it a crucial component of the functional foods industry. In conclusion, spirulina offers high nutritional value and potential health benefits that align with present consumer trends. With further advancements in food processing and formulation, spirulina-based protein bars are poised to become a popular choice in the health food market.

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AI BASED PRECISION SEEDING TECHNIQUES FOR MAXIMIZING CROP PRODUCTIVITY WITH MINIMAL INPUTS

Mohd Reyaz Ur Rahim*, Faiz Mohd,
Mohd Faizan Hasan, Syed Ali Husain Jafri and Mohd Anas
Department of Mechanical Engineering,
Integral University, Lucknow
*Corresponding author E-mail: rrahim@iul.ac.in

Abstract:

Traditional agricultural practices face significant challenges, including resource inefficiency, environmental degradation and suboptimal yields, compounded by rising global food demand. Precision agriculture offers a sustainable alternative by leveraging technologies like GPS, IoT and data analytics to optimize farming practices and reduce the lavish use of inputs such as water, fertilizers and seeds, while maintaining or improving crop output. This paper reviews the application of AI based precision seeding techniques as a promising subfield of precision agriculture. AI and Machine Learning (ML) algorithms utilize real time data from soil sensors, satellite imagery and weather forecasts to dynamically adjust seed selection, placement, depth and density according to local field conditions. This approach addresses the inefficiencies of uniform seed dispersal, ensuring optimal resource use and significantly enhancing crop establishment. The literature indicates that AI controlled precision seeding yields substantial benefits, including an increase in overall yields by 10–15% and crop emergence by up to 15%, alongside a reduction in seed usage by up to 20% compared to conventional methods. Key applications include optimizing seeding depth and spacing, autonomous seeding machinery and Variable Rate Seeding (VRS). Despite the clear advantages in productivity, efficiency and environmental sustainability, significant limitations persist. These include the high cost of implementation, challenges in data quality and integration and a lack of technical expertise and scalability, particularly for smallholder farmers. Strategies to overcome these barriers involve developing cost effective, adaptable AI models, improving rural data infrastructure and implementing comprehensive training and support programs. In conclusion, AI based precision seeding presents a transformative approach to meet the increasing global food demand sustainably, provided that concerted efforts are made to address the technological and economic barriers to widespread adoption.

Introduction:

Agriculture is indeed facing vast challenges due to the increasingly large number of people in the world as well as the equally increasing demand for food, which results in inefficiencies lavish use of natural resources, degradation of the environment and suboptimal crop yields. Precision agriculture emerges as an alternative approach to overcome these problems through the use of modern technology such as GPS, iot and data management tools. Such technologies help optimize agricultural practices, with reduced consumption of inputs that depend on much water, fertilizers and seeds while maintaining or improving crop yields [1].

One area of precision agriculture promising much is precision seeding, which applies AI and ML algorithms in the selection, placement, depth and density of seeds. The traditional method of seed dispersal, in large and uniform areas, has problems such as overuse of seeds, uneven establishment of crops and poor resource allocation [3]. Conversely, precision seeding based on AI uses real time data to derive strategic planting techniques aimed at reducing usage and intensifying yield [4].

Precision seeding with the ability to dynamically adjust the depth and spacing in relation to the local soil composition, moisture and conditions of the environment [5] has been made possible by AI. It will ensure the optimal use of the resources available while increasing the chances of successful establishment of the crop many folds. The application of AI in the farming domain depends considerably on multiple data sources related to soil sensors, satellite images and weather forecasts for the optimization of the strategies concerning planting in local field conditions [6].

Most AI algorithms use a different approach by mainly using neural networks and others such as decision trees and support vector machines to consider a large amount of data in the hope that one will predict the best strategies to be followed for seeding crops and their conditions. For instance, the machine learning model can learn from previous yield data and also soil composition in order to tweak the density of seeds used in seedings so that input cost is fully minimized and the highest productivity level is achieved [7]. It not only saves efficient sowing but also proves a sustainable approach as water, fertilizers and pesticides that are vastly used in the conventional farming are not being overused.

AI and ML have been designed to increase crop yields and reduce resource utilization. Compared to the traditional practices, AI controlled precision seeders have research that AI seeding has increased crop emergence by 15%, overall yields by 10 15%, reduces seed usage to 20% of the conventional methods [8]. More so, precision seeding is also bound to restrict the potential negative environmental effects that may be occasioned by the process of over seeding or under seeding which is normally characterized by establishing crops shoddily and wasting resources [9]. Fig. 1 shows the mind map of AI driven precision agriculture and how it is interconnected with others.

High accuracy for AI driven precision seeding has been supported by various studies. For instance, crop yields and seed wastage were highly improved in comparison to AI based seeding systems according to Padhiary *et al.* [10]. According to Bhat *et al.* [11], productivity of crops increases by 12% as input costs decrease by 20% due to AI optimization of seeding density and spacing in comparison with AI based seeding systems. All these indicate that AI is actually working towards a general revolutionary change in agriculture and, therefore, in its applications more resource effective and sustainable.

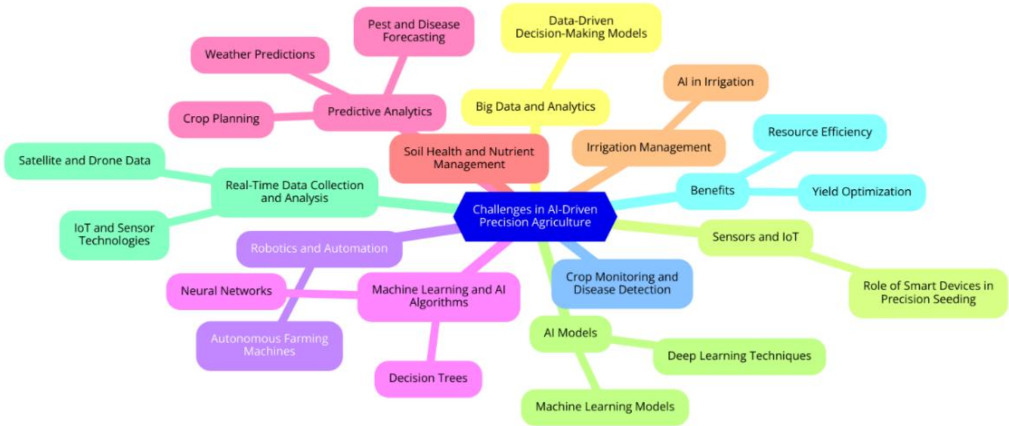

Figure 1: Challenges in AI Driven Precision Agriculture using a mind map

Precision seeding is AI farming: machine learning is now implanted in real time data collection and analysis a step closer to modern agriculture than ever before. The technique comes with immense promise for improvements in crop productivity and, at the same time, on reduced environmental footprint of farming systems. The following sections expand further on the techniques, methodologies and outcomes achieved through resource optimization and sustainability on the basis of AI based precision seeding.

Literature review methodology

A literature review was done to look at AI based precision seeding techniques to maximize yield with minimum input. A multi stage approach was used, selecting databases, formulating search terms and filtering studies based on pre determined inclusion criteria.

1. Data sources and search strategy

Peer reviewed articles, conference papers and patents were sourced from top academic databases including Google Scholar, Scopus, Web of Science and IEEE Xplore. These databases were chosen for their large collection of scientific and technical literature on artificial intelligence, machine learning and precision agriculture. Scopus was chosen for its broad coverage of agricultural engineering and AI related publications [12]. Besides these databases, Elsevier and Springer platforms were also consulted to get the latest and most credible research.

The inclusion criteria for this review were based on specific search terms such as “AI in precision agriculture”, “machine learning for precision seeding”, “AI driven crop yield optimization” and “AI based resource optimization in agriculture”. These keywords were combined using Boolean operators to get the articles directly related to application of AI in precision seeding.

Separate searches were also done for specific AI models such as neural networks, decision trees and support vector machines to see how these algorithms contribute to crop productivity through intelligent seeding.

2. Inclusion and exclusion criteria

The selection criteria for articles review were clearly set with a defined set of inclusion and exclusion criteria to only include the most pertinent insightful studies.

Inclusion criteria:

- Timeframe: Review is limited by AI technologies from 2015 to 2024 and breakthroughs and recent developments in that time frame.
- Focus on AI in Precision Seeding: Literature is narrowed to the particular application of AI and machine learning for the techniques applied in precision seeding.
- Quantitative Analysis: It was preferred if such studies reported at least some quantitative measure related to the impacts of AI based seeding on crop productivity, resource optimization, or environmental benefits.
- Wider Perspectives: Generalist but informative reviews and meta analysis exploring the increasing role of AI in agriculture were also included if they would help in understanding AI based sowing techniques.

Exclusion criteria:

- Traditional Agriculture: Articles that deal only with traditional agriculture but do not incorporate AI were excluded.
- Pre 2015 Studies: Papers published before 2015 were excluded unless they offered foundational insights into the development of precision agriculture technologies.
- Empirical data: This would remove studies based on theoretical models, without any practical application or with no empirical data in the agricultural settings.

3. Bibliometric and content analysis

Related authors and publications' interests and keywords in the area of AI based precision agriculture. There is high growth concerning the publication associated with the application of AI based agricultural technology with precision seeding and crop management. Figure 1 of the literature review shows that research output between the years 2017 and 2024 using ML and AI vision gains high interest [13].

Content analysis was also undertaken to determine the dominant themes and trends in the literature. Major themes that emerged are listed as follows:

- Accuracy Seeding AI Algorithms Research on neural networks, random forests, reinforcement learning for optimal seed placement and density [14].

- Resource Optimization: Research on how AI driven seeding technologies reduce usage of seeds, water and fertilizers while yield increases [15].
- Environmental Impact: Papers on reducing agricultural input wastage and carbon footprint through intelligent resource management [16].

4. Selected studies for review

After application of the inclusion and exclusion criteria, 105 articles are selected for intensive analysis. These research studies provided key insights related to the role of AI in precision seeding in enhancing yield, reducing inputs and sustainability. This consisted of experimental studies, case studies and reviews that assessed the performance of AI models in agricultural settings [17]. Among the flagship studies, which have been summarized by Padhiary *et al.* [18], one core study is that, in all-terrain vehicles, machine learning algorithms are integrated to adjust seed delivery and planting depth based on soil variability and historical yield data. Results from such research proved that AI maximally improved the consistency in crop establishment, yielding 15 20% increases in production and 25 30% overall investment reduction [19]. Another research by Avalekar *et al.* [20] indicated how AI based seeding models, relying on real time soil data, decreased seed waste to 20%, while crop productivity was at satisfactory levels.

5. Limitations of the reviewed studies

While most the reviewed studies yielded positive results in terms of productivity and resource optimization, several limitations were observed. Many studies had no long-term data regarding the sustainability of AI driven precision seeding, especially over different geographical settings. Moreover, frequent scalability challenges were mentioned because AI technologies are still very expensive and inaccessible to small farmers, especially in developing countries [21].

6. Future research directions

By reviewing these literatures, some areas are suggested for future research.

Improvement in the scalability of AI based precision seeding systems so that it becomes more accessible to smallholder farmers.

Developing low-cost AI models and sensor technologies to reduce the entry barrier for AI adoption in agriculture.

Study the effects of seeding AI driven systems across seasons and different climatic conditions over a period of several years [22][23].

Applications and benefits of AI based precision seeding

One of the most promising innovations in precision agriculture includes AI based precision seeding. Algorithms and ML models optimize seeding depth and spacing, as well as timing, depending on up-to-date knowledge of sources from soils to weather forecast data and satellite images. This section discusses some key applications of AI based precision seeding and the consequent advantages it brings to crop productivity, resource utilization efficiency and sustainability.

1. Applications of AI based precision seeding

1.1 Optimizing seeding depth and spacing

One of the most important uses of AI in precision seeding is optimization of seeding depth and spacing. Based on data generated by soil sensors, historical yield records and environmental conditions, machine learning models make recommendations for ideal seed depth and spacing. In this way, each seed is planted under optimal conditions with good chances for germination and healthy crop growth. AI models, such as neural networks and random forests, can make real time decisions on seed placement by going through large datasets of soil characteristics and moisture content [24].

For instance, Upadhyay *et al.* [25] demonstrated that ATV based seeding system allowed an AI technology seeding mechanism of seeds to increase placement accuracy in seed. AI driven algorithms were used in the system and regulated depth of seeding based upon the conditions specified to deliver consistent crop establishment with improved yield.

1.2. Automated seeding machinery

Another important area of AI based precision seeding is autonomous seeding equipment. AI system equipped automated tractors and drones can perform the tasks of seeding in almost full auto, which significantly increases both accuracy and efficiency. The machines may work on their own, making real time adjustments to their operations based on data about the soil and environment.

According to the review done by Sharma *et al.* [26], the AI based autonomous seeding system reduced the labor cost while sowing seeds under the most favorable conditions. These systems made use of reinforcement learning as well as real time feedback in order to adjust themselves according to the changes in conditions prevailing in the fields, thereby improving seed germination and crop uniformity.

1.3. Variable Rate Seeding (VRS)

Variable rate seeding is another vital application of AI in the adjustment of seeding rates in various zones of a field. The AI model will use data relating to soil fertility, moisture levels and previous yields to adjust the ideal seeding rate for the given section of the field to utilize the most resources it possibly can. VRS reduces seed wastage in poorer soil quality areas while increasing seeding density in those regions of the area holding higher potential productivity.

Benos *et al.* [27] worked on developing an AI based VRS system for a cornfield and showed a 12% increase in yield based on variation in seeding density along with the variability in soils. The current project helped optimize resource allocation and seeds to realize maximum productivity.

1.4. Crop health monitoring and disease prediction

Besides optimizing seeding, AI based precision seeding systems can be combined with crop health monitoring systems using machine learning to predict diseases as well as other stresses that will affect crops at any point during the growth period. These systems monitor the crops through satellite imagery, drone data and soil health sensors to prepare in advance for likely threats. Early intervention helps introduce timely interventions, including adjusting seed rates or applying fertilizers and pesticides, to protect the crops and ensure maintainable levels of high productivity.

Crop disease prediction has been done by research carried out by Mohanty *et al.* [28] on AI models, depending upon agricultural crop growth patterns and environmental conditions and crop losses were decreased up to 20% by more specified targeting in seeding and treatment.

2. Benefits of AI based precision seeding

2.1. Increased crop productivity

The third one is the precision seeding, which involves AI based an ultimate truth of increasing crop productivity through the optimal placement of seeds. Precise seeding determines seeding depth and spacing as well as timing within the real time data obtained by considering the best factors for seed germination and growth. According to research evidence, precision seeding results in better plant density, superior crop uniformity and higher resistance to environmental stress [29].

For example, Subeesh *et al.* [30] showed that the crop yield was increased more significantly by using AI based seeding technique compared to a traditional seeding technique. The AI model helped optimize the location of seeding based on the surrounding soil conditions for improving the health and productivity of crops in general.

2.2. Resource efficiency and cost savings

A most important advantage that AI driven precision seeding gives farmers is input reduction through seed, water and fertilizer. By changing seeding density and placement to meet specific needs for each particular zone of a field, wastage of resources can be minimized. AI can calculate the number of seed needed for each specific area and avoid over seeding on low yielding regions and under seeding on potentially high areas.

The seed usage was reduced by 20% and the costs saved by the farmer with AI driven seeding systems based on a field trial conducted by Karunathilake *et al.* [31]. The study also revealed water and fertilizer reductions by 25% through the effective distribution of resources according to soil data.

2.3. Environmental sustainability

AI based precision seeding contributes to environmental sustainability because it curtails overuse of agricultural inputs like water, fertilizers and pesticides that bring harm to ecosystems.

Precision seeding ensures inputs are applied where they are fully utilized and runoff and soil degradation is very low.

Sharma *et al.* [32] has referred to research talking about the implementation of AI driven precision agriculture practices for cutting 30% fertilizer applications and 25% pesticide applications, thus significantly minimizing the farming practice's environmental footprint. With less chemical use, precision seeding also saves soil health and biodiversity.

2.4. Labor efficiency

Automated AI based seeding systems can perform complex seeding tasks with minimal human intervention, reducing labor costs and freeing up farmers to focus on other important tasks. AI powered machinery can work autonomously, making precise adjustments in real time without requiring manual oversight.

The use of AI driven seeding systems reduced the need for manual labor, enabling farms to operate more efficiently and at lower costs [33]. This is particularly beneficial for large scale farms, where seeding is a time consuming and labor-intensive process.

Data collection and analysis techniques

An effective method of successful collection and analysis of data is an essential part of AI based precision seeding. The ability to gather large volumes of data for processing and real time analysis is what allows AI models to make decisions that will best optimize seeding depth, density and resource use. Techniques applicable in data collection and analysis in AI driven precision seeding systems are discussed with an emphasis on how they enhance crop productivity and resource efficiency, thus enhancing sustainability.

Data collection techniques

1. Soil sensors and field sensors

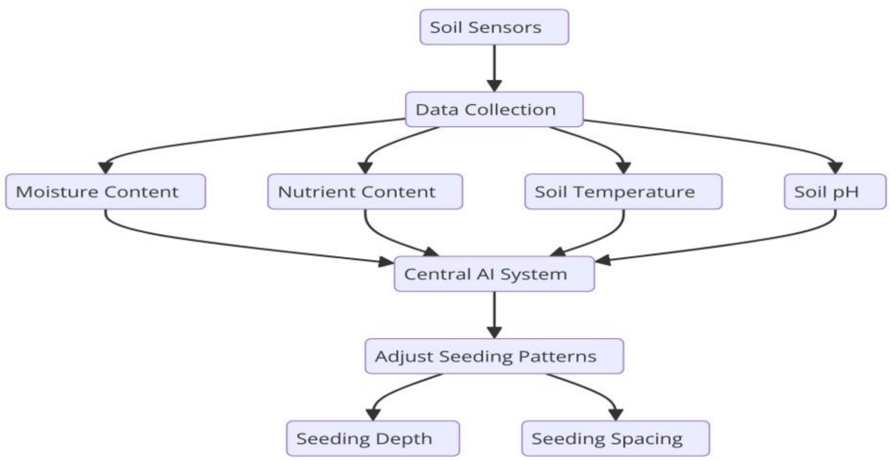

Figure 2: Soil sensor flowchart

Measurement of some of the soil parameters like moisture content, nutrient content, temperature and pH can only be perfectly known through soil sensors. These sensors are spread all over the field to monitor real time conditions constantly. This collected data is sent over to central AI systems that adjust seeding patterns, depths and spacing according to it. Fine tuning the AI model with high resolution data means placing seeds in optimal conditions for germination and growth. Fig. 2 shows the flow chart of soil sensor.

According to Liu *et al.* [34], AI based systems that integrate soil sensors can accurately monitor soil variability, providing valuable inputs to machine learning algorithms that optimize seeding practices. By using real time soil data, precision seeding systems can adjust parameters such as seeding depth and spacing to match the specific conditions in each part of the field.

2. Satellite and drone imagery

Remotely sensed data using satellite and drone imaging technologies are an integral part of crop growth, field variability and soil health assessment. Images taken by satellites or drones over fields are then analyzed by AI algorithms to track crop health, detect stress conditions and identify spots that may require reduction in seeding rates. Multispectral and hyperspectral imaging can indeed obtain detailed information related to crop vigor and identify early signs of disease or nutrient deficiency. Fig. 3 is particularly focusing on the use of satellite and drone imagery for crop analysis.

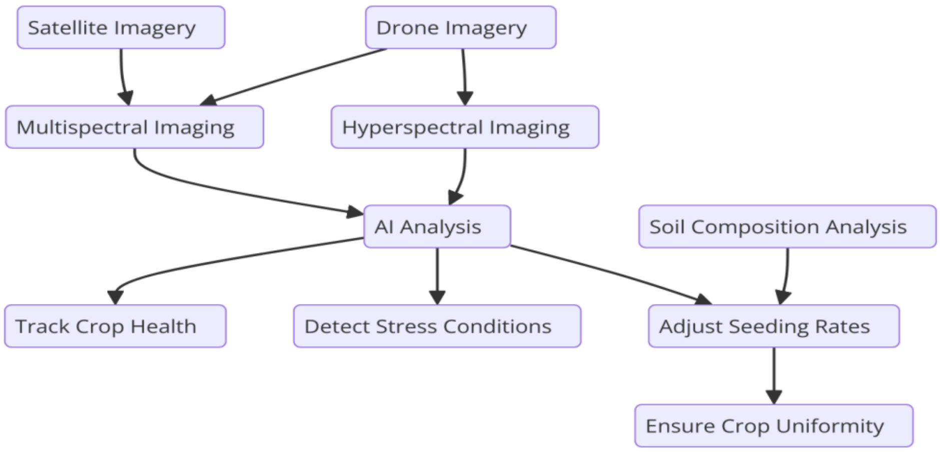

Figure 3: Satellite and drone imagery for crop analysis

Several research works on the integration of drone based imagery with AI systems have demonstrated that the accuracy levels for seeding and resource management are increased. For instance, Raj *et al.* [35] demonstrated the use of drone imagery for soil composition and variability analysis, which allowed the AI system to alter seeding density and placement according to the characteristic features found in the soil. This had the strong effect of seed wastage minimization while ensuring uniformity in crops.

3. GPS and geospatial data

One of the core technologies to this precision seeding is GPS, which can facilitate an AI based machinist to work with high precision even in complex fields. Geospatial data gathered from GPS has been used to map field boundaries, topography and specific areas requiring differentiated seeding strategies. Soil sensor data is used in a complementing manner with GPS data to create detailed field maps that are fed into an AI model for making decisions about seeding.

Khan *et al.* [36] also discussed how GPS systems assist in guiding autonomous seeding machinery. AI driven tractors that employed GPS data navigated fields and accurate adjustments in seeding within fields to optimize the process for overall efficiency. Such guidance systems enable consistent seed placement while eliminating overseeding, thereby conserving inputs and increasing productivity.

4. Weather stations and environmental sensors

Another crucial component of AI driven seeding systems is live weather information. Weather stations are placed on fields. These monitor the temperature, humidity, rainfall and the speed of wind among other elements. The collected data is then used by AI algorithms to make adjustments in the seeding procedures based on the variance that exists in the climate. For example, if it is going to rain, AI will stop the procedure of seeding to avoid soil erosion or water logging. On the contrary, however, in dry conditions, AI could suggest deeper seeding so that the moisture reservoirs in the soil may be reached.

An example of how the weather has been integrated into AI based seeding systems was demonstrated by a work by Pierre *et al.* They presented how predictions on the optimal seeding window, based on local climate conditions, had been made by AI models to ensure that seeds were sown in their right time for better germination rates and crop establishment.

Data analysis techniques

1. Machine learning algorithms

AI Precision Seeding bases its core in machine learning algorithms. The basic types of machine learning used in farming are supervised learning, unsupervised learning and reinforcement learning. These algorithms analyze big data inventories from sensors and satellites and records about historical crop yields to predict the best seeding patterns, depths and densities that make the maximum yield. The most commonly used neural networks, SVMs and decision trees provide crucial support to extract actionable insights from big data.

According to Fernandes *et al.* [38], neural networks can be used to analyze soil moisture and nutrient content, thereby creating the ability to make real time adjustments in depth and spacing of seeding. Because of such models, crop yields increased by 15 20%. Machine learning models also continue to learn from previous planting seasons and time continue to refine their predictions over time to improve performance.

2. Data fusion and integration

Data fusion is the fusing of data from various sources, like soil sensors, weather stations, satellite images and historical crop data. AI models are based on data fusion techniques that help to create a holistic view of the condition in the field. Based on this holistic approach, AI systems can take more informed decisions because they consider the soil quality, patterns of weather and the history of crops.

Mehedi Shaikh *et al.* [39] stressed that data fusion can be an important tool for AI in precision seeding. Combining the data from soil sensors with satellite images and weather forecasts, AI based systems optimized seeding strategies, thus enhancing crop performance and minimizing the use of costly inputs. With multiple streams of data fusing together to form a more accurate presentation of field conditions, such a seeding process had overall efficiencies enhanced through precision.

3. Predictive analytics

The predictive capabilities of an AI system help the system make accurate predictions about future states of affairs and adjust its seeding strategy accordingly. Based on a prior history, weather conditions and soil status, AI models will predict the best time to plant, seeding density and resources required per field. Predictive models also assist the farmer in the coming period in anticipating all possible challenges, such as drought or infestation and enables ample time to take appropriate precautions during the planting season.

Fuentes *et al.* used predictive analytics in precision seeding in a case study [40]. Using crop data and past weather trends, the AI system could determine the ideal time to seed corn fields. Thus, there was an increase of 12% in crop yields and 20% in resource use as the operations were carried out under ideal conditions.

4. Geostatistical analysis

Geo statistics can handle spatial variations within the fields. So, mapped soil properties, moisture and fertility can be managed across different zones, wherein site specific seeding strategies can be followed with the aid of geo statistics. AI models may divide the fields into management zones through geo statistics and apply variable rate seeding techniques on such a basis.

Hilal *et al.* [41] worked on integrating geostatistical analysis to identify high potential areas in the fields and adjust seeding density accordingly. By embedding geostatistical information into AI based models, seed efficiency improved by 25% and crop yield increased in the under seeded area.

5. Deep learning for image analysis

Image classification with the help of drones and satellites involves deep learning techniques, particularly CNNs. The models can identify patterns relating to soil moisture, plant health issues and nutrient deficiencies through aerial images. Deep learning is also used to recognize crop growth anomaly situations and optimize AI systems for adjusting seeding operations according to specific requirements.

The study of Canicatti *et al.* [42] made use of CNN to analyze the images acquired using drones to detect under coverage areas in the field where crop vigour is lower. According to this information, the AI system modified the planting density during subsequent cycles such that the crops are better distributed and yielding well.

Challenges in data collection and analysis

While the AI based precision seeding system has many advantages with regards to data collection and analysis, many challenges here:

- Data Quality: The quality of data along with data granularity of what is being collected by the sensors decides the accuracy with which AI models are making decisions. Poor placement of sensors and equipment that is deficient in data can sometimes give misleading inputs to seeding decisions [43].
- Data Integration: The unification of data from information sources such as sensors, satellites and historical records is possible with the help of complex data integration techniques. Incomplete and inconsistent data are likely to degrade the performance of AI models [44].
- Sensors and data infrastructure expenses: very high setup and maintenance costs for sensors, weather stations and drones limit the use of AI driven seeding technologies, even for small farmers 45.

Limitations of AI based precision seeding

AI based precision seeding is showing great promise for increasing agricultural productivity, efficiency and sustainability. However, the system does suffer from certain drawbacks that limit its enormous scale adoption. These draw backs are technological, economic, environmental and social challenges, which must be addressed to fully unlock the potential of seeding technologies driven by AI.

1. High cost of implementation

State of the art precision seeding by AI driven technology require more investment in terms of finance. High end equipment, like autonomous tractors, high precision sensors, drones and weather stations, is quite expensive, especially for small scale farmers or small agricultural enterprises in developing countries. Installation, maintenance and calibration are further burdening the entire operational cost.

According to Smidt and Jokonya [46], the main hinderance to the adoption of digital technologies by small scale farmers, especially in areas like South Africa, has been the high cost of initial investment as well as a lack of cheap infrastructure. As noted, this economic barrier limits many farmers from accessing the benefits of AI based precision seeding toward wider application in agriculture.

2. Data availability and quality

The quality and availability of data also dictate the effectiveness of the AI models for precision seeding. What AI algorithms need is a lot of datasets, including real time data on the health of the soil, weather patterns, historical yield information and geospatial data through which decisions concerning seeding can be accurately determined. However, in the case of most rural and underdeveloped regions, there is not enough infrastructure for collecting and transmitting high quality data.

Outlier or missing data could lead to poor seeding recommendations, thereby potentially lowering AI system performance. Albahri *et al.* [47] believed that the inability to utilize accurate high resolution data is a significant challenge for AI models. Also, without proper weather monitoring and connectivity in certain areas, the AI model may deteriorate its decision making capabilities. In addition, the data variabilities across geographic locations pose challenges to AI models trained specifically with specific datasets, thus limiting the ability of applying solutions in various, very heterogeneous agricultural landscapes.

3. Data integration and complexity

Improving that would be the integration of information coming from different sources, such as soil sensors, drone imagery and weather stations into a single AI system. Data coming from different platforms are often in many different formats and the lack of standardization can make merging datasets difficult, thus potentially causing delays or wrong real time decisions during seeding operations.

Homssi *et al.* [48] drew attention to the fact that data integration is challenging with problematic synchronization between streams of satellite image data and sensor networks along with environmental models. Hence, such integration becomes inefficient in the precision seeding process and also decreases crop productivity due to the failure of systems to correlate all relevant data in a manner to give real time recommendations.

4. Lack of technical expertise and training

The deployment of AI driven precision seeding technologies requires a high level of technical expertise, both in terms of operating the equipment and understanding the underlying algorithms. Farmers, particularly in regions with limited access to educational resources or technical support, may struggle to adopt and effectively utilize these advanced systems. This knowledge gap limits the accessibility of precision seeding technologies, especially for small scale and subsistence farmers.

Obasi *et al.* [49] pointed out that even when AI based systems are made available, many farmers lack the technical knowledge to effectively use the tools. Training programs are often inadequate and the complexity of AI systems can discourage adoption, leading to underutilization of the technology. This barrier is particularly pronounced in regions where there is limited infrastructure for ongoing training and support.

5. Environmental and geographic limitations

Although it may work well in one context, AI precision seeding may not become as easy to adapt to another. For example, AI models rely mostly on history and real time environmental inputs and such systems are easily disrupted by unpredictable weather conditions such as heavy rainfall and droughts. The soil types and climatic conditions, with varied characteristics across different regions, also make the development of universally applicable AI systems difficult.

Other geographical limitations include mountainous topographies or complex land shapes. Autonomous machines, like tractors and drones, may be hard to operate or navigate in such terrains. As Runck *et al.* [50] find, the movement and performance of seeding machines partly get affected by topographical heterogeneity, especially in heterogeneous landscapes. Such a geographical constraint might reduce the efficiency by as much as the useful agricultural conditions.

6. Scalability and accessibility

Scalability is another limitation of AI based precision seeding. Large agricultural enterprises, well funded and with resources to invest in the adoption and scaling of AI driven technologies, are few in number. Medium scale to small farms has a lack of capital and infrastructure to engage with such technologies. Technologies are limited to accessibility in rural and underserved geographies and costs associated with extending these systems over larger geographical areas prove inhibitory.

Smidt and Jokonya discuss how digital infrastructure in rural areas often constrains the scaling of precision farming technologies. Such a limitation brings up a strict dichotomy between big commercial farms and smallholders regarding who benefits from the advancements in AI driven seeding technologies.

7. Ethical and social concerns

The introduction of AI into agriculture sparks debate with issues on the need to handle job displacement, ethical concerns and social implications. It reduces the necessity to employ human labor while resulting in displacing farm workers engaged in traditional farming jobs as automation machines and AI driven systems take over the sector. Once more, the digital divide exacerbates the already existing imbalance concerning agricultural productivity and income for those with or without the access to technology.

Moreover, data protection issues will arise due to immense volumes of sensitive information farms generate with the technology developers and AI itself. The control of the data owned by the farmers will determine the ethics of using AI in farms.

Strategies to overcome limitations of AI based precision seeding

In actual complete potential of AI driven precision seeding technologies, therefore, would be anchored on strategic approaches that should address issues identified with the current limitations. Such strategies fall under the headings of technological advancement, economic incentives, data management practices, education and training programs and ethical frameworks by focusing on these areas, making precision seeding more accessible and effective for small scale and marginalized farmers.

1. Cost effective technologies and subsidies

To lower the financial barriers to adoption, there is a need for the development of cost effective technologies that can deliver similar benefits at a fraction of the cost. Initiatives such as government subsidies, grants and low interest loans can provide financial support to small scale farmers. According to Papadopoulos *et al.*[51], targeted financial incentives can help bridge the economic gap, enabling broader adoption of digital technologies in agriculture.

2. Improving data infrastructure and quality

Enhancing the infrastructure for data collection and transmission is crucial. Investments in local data collection systems, such as community based weather stations and soil monitoring networks, can improve data availability and quality. Collaborative efforts between governments, NGOs and private sector partners can facilitate the establishment of reliable data ecosystems. As noted by Padhiary *et al.* [18], robust data infrastructure is essential for the effective functioning of AI models in precision agriculture.

3. Standardization and integration frameworks

The integration of data processing needs standardized protocols for sharing and interoperability among different systems. Common data formats can be established to easily fuse datasets from various sources into a seamless fusion, enabling real time decision making capabilities. Boujdi *et al.* [52] stresses the need to develop the integration framework that will seamlessly interact with other technologies, ensuring better precision seeding operation processes.

4. Comprehensive training and support programs

Because of the knowledge gap to be filled, comprehensive training and support programs are necessary for the adoption of AI technologies. Such trainings which allow trainees to apply skills practically, have on the job education and are of great importance since they empower the farmers to handle the advanced systems in an effective manner. Tailor made training that takes care of local context and challenge conditions is very important, according to Stringer *et al.* [53].

5. Adaptable AI models for diverse environments

Developing adaptable AI models that account for geographic and environmental variability can enhance the applicability of precision seeding technologies. Research should focus on creating models that are flexible enough to adjust to local conditions, such as soil types and weather patterns. By utilizing localized data and machine learning techniques, AI systems can provide more accurate recommendations across diverse agricultural landscapes.

6. Scalable solutions for smallholders

Scalable solutions that will allow smallholders to use high end precision seeding for their benefit in having AI driven precision seeding will be of prime importance. Cooperative models will consider how such resource sharing and technological sharing can ensure better access and affordability. Smidt and Jokonya propose that encouraging cooperative arrangements can enable smaller farms to avail advanced technologies without the prohibitiveness of costs.

7. Ethical principles and data governance

There is a need for guidelines and frameworks of data governance among the ethical concerns related to the use of AI in agriculture. Farmers should have control over their data and benefits from its use for them to trust these emerging technologies. Issues related to data privacy and usage in policy implementation can assuage exploitation anxieties while providing equitable access to AI advancements.

When these approaches are applied, stakeholders work toward achieving the most optimal outcome to deal with the limitations that AI based precision seeding can impose on agriculture productivity, sustainability and equity.

Conclusion:

One of the major developments in the modern scene of agriculture is supposed to be developing and using AI based precision seeding. They might be causing changes in crop production, resource management and environmental sustainability with higher algorithmic sophistication and machine learning models. The data availability on soil moisture, satellite images and weather forecasts in real time to optimize seed placement, depth and density through AI based precision seeding is believed to be materialized.

This is the key advantage of precision seeding with AI, where such seeding strategy would be altered according to a particular section of the field. Seeding strategies typically are uniformly applied to a number of different types of soils and settings and one can easily identify the inefficiencies associated with this technique, including seed wastage and uneven crop establishment as well as less than optimal use of resources. Instead, AI based systems apply data analytics on seed placement to ensure that every seed is planted under the best conditions. This will not only maximize the emergence and growth of crops but also minimize environmental effects caused by farming practices through repressed abuses of water, fertilisers and pesticides.

However, recent research has pointed out that tangible advantages represent the case with AI driven precision seeding. Researchers have discovered that such systems increase yields by 10 15% and emergence rate by up to 15%. In addition, compared with traditional sowing, they use 20% less seeds. Environmental sustainability is also advanced by AI based precision seeding because fertilizers and pesticides entry into water decreases and consequently, soil health is protected. This reduces carbon footprint of agricultural operations.

However, despite such promises, several challenges are there for the technological adoption of AI based precision seeding, especially among small scale farmers and in developing regions. Cost is one of the challenging issues today the expensive cost of having autonomous machinery, sensors and data infrastructure underpins much of the challenge. Moreover, the effectiveness of the AI models is severely dependent on the quality and availability of data, which often is a lack in the rural and underdeveloped areas. In any case, technical challenges also relate to the integration of diversified data sources such as sensors measuring soils, unmanned aerial vehicles and weather data in that operating these complex systems will require specific expertise and qualifications.

Moreover, geographical and environmental conditions are also limiting factors in terms of scalability of AI based precision seeding. The aforementioned technologies may be effective in a few settings but might not perform the same or similarly in other settings, mainly those areas where the topology is complex or areas where there is less predictability with regards to weather. Other challenges in the use of AI in agriculture include ethical issues regarding job dislocation and data privacy.

Specific strategies must then be devised for such limitations. These would include making these AI technologies cheaper through subsidies and low cost model designs, bettering data infrastructure in rural spaces and having standardized protocols for the integration of data. There will also have to be training and support programs that are all thorough, to equip the farmers with the skills necessary to use the systems effectively on their end. Therefore, research needs to be conducted toward better development of adaptive AI models so they can account for geographic and environmental variability to ensure applicability of precision seeding technologies in a wide range of agricultural landscapes.

In conclusion AI based precision seeding is the transformist approach to agriculture with colossal benefits in terms of crop productivity, resource efficiency and environmental sustainability. While big challenges still stand at these fronts cost, availability of data and scalability research and development continue with further targeted support for farmers, all of which shall unlock these full potentials. Regarding this, AI integration in precision agriculture promises to meet the ever-increasing global demand for food while preserving natural resources and encouraging sustainable farming practices.

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MAJOR DISEASES OF BANANA (*MUSA* SPP.): ETIOLOGY, EPIDEMIOLOGY, DIAGNOSIS, AND INTEGRATED MANAGEMENT – A COMPREHENSIVE REVIEW

Aniket Anil Kshirsagar
Maharashtra Mahavidyalaya, Nilanga, Latur
Corresponding author E-mail: aniketkshirsagar842@gmail.com

Abstract:

Banana (*Musa* spp.) is a staple fruit crop and an important source of livelihood in tropical and subtropical regions. Production is threatened by a number of diseases caused by bacteria, fungi, viruses, nematodes and post-harvest pathogens altogethe causing large economic losses and threatens food security. This review presents current knowledge on major banana diseases including Fusarium wilt (Panama disease), black and yellow Sigatoka, banana bunchy top disease, bacterial wilts (Moko and BXW), nematode infestations (notably *Radopholus similis*), and crown/anthracnose rots and discusses their etiology. epidemiology, diagnosis, and conventional and modern management strategies. This review emphasizes on integrated disease management (IDM): sanitation and clean planting material, cultivar resistance and breeding, tissue culture for pathogen-free planting stocks, biological control agents, targeted chemical use, and emerging biotechnology (transgenics, genome editing, RNAi,). The review also highlights advances in molecular diagnostics, remote sensing for disease surveillance, and socio-economic challenges for implementation of control measures. Finally, we identify research gaps and priorities for sustainable banana disease management.

Key words: Banana Diseases, Control Measures, Molecular Diagnostics, RNAi, Transgenics, Genome Editing.

1. Introduction:

Banana (*Musa* spp.) is cultivated globally across more than a hundred countries and plays a vital role in nutrition, income generation, and food security in many small-scale farming systems. However, banana production is particularly vulnerable to infectious diseases due to the crop's largely vegetative propagation and the clonal dominance of a few cultivars (e.g., Cavendish), which limits genetic diversity and heightens risk from aggressive pathogens. Recent decades have seen the emergence and spread of this devastating pathogen and global threats to banana production and trade (Blomme *et al.*, 2017).Other prominent disease are,Yellow Sigatoga (Cook *et al.,* 2013), Black Sigatoga (black leaf streak) (De Bellaire *et al.,* 2010), Xanthomonas wilt (Tripathi *et al.,* 2009), banana streak (Dahal *et al.,* 1998), banana bunchy top (Dale, 1987).These diseases cause huge losses in banana crop production and devastatingly affect food securit y (Drenth and Kema, 2021). Effective surveillance by timely detection using novel rapid techniques will enable the development of more efficient control measures (Christaki, 2015). This review focses on current scientific understanding of these diseases, their etiology, epidemiology, diagnostic advances, and integrated management strategies, most notable among them *Fusarium oxysporum f. sp*. cubense (Foc) tropical race 4 (TR4), the Sigatoka complex, and virus- and bacterium-mediated wilts which together pose both low crop yield and poor quality fruits, to overcome these problems, efforts must be taken to create awareness among banana growers about eco-friendly pest control methods and the integration of tissue cultured bananas with improved crop management practices for sustainable banana production (Kabunga *et al.,* 2014). Moreover, focus on regulatory hurdles and public perceptions is pivotal for embracing genetically engineered bananas (Pua *et al.,* 2019).

2. Major fungal diseases:

2.1 Fusarium wilt (Panama disease):

Etiology and biology. Fusarium wilt of banana is caused by Fusarium oxysporum f. sp. cubense (Foc). Distinct biological lineages (races and vegetative compatibility groups), including the widely damaging TR4 (often referred to as Fusarium odoratissimum in recent taxonomic treatments), exhibit differing host ranges and aggressiveness. Foc is a soilborne, vascular pathogen that colonizes roots and moves into the rhizome and pseudostem, producing vascular discoloration and leading to external symptoms such as yellowing, leaf wilting, and eventual plant death. The microsclerotia and chlamydospores allow long-term persistence in soils (Jackson *et al.,* 2024; Pegg *et al.,* 2019).

Symptoms and diagnosis: Early symptoms include one-sided yellowing of older leaves. eventually wilt and reduced bunch size; advanced infection shows splitting of pseudostem and brown-to-black vascular streaking. The plants will eventually die and the plant does not produce any fruit bunches. TR4 may also cause other symptoms, including bulging and splitting of the pseudostem and necrosis of the emerging heart leaf. Diagnosis is based on symptom assessment plus laboratory methods: isolation, morphological identification, PCR-based assays, and increasingly sequencing and molecular markers (Jackson *et al.,* 2024, Diksha Sinha. 2022).

Epidemiology and spread: Foc spreads through infected planting material, contaminated soil, water, farm equipment, and movement of infested planting materials and soil. It can survive p to 30 years in soilThe durability of spores in soil poses problems in use of site sanitation and crop rotation as solo methods. Transcontinental spread of TR4 showcases the need for biosecurity and coordinated surveillance (Blomme *et al.,* 2024, Jackson *et al.,* 2024, Disksha Sinha, 2022).

Management: Control relies on integrated approaches: deployment of resistant or tolerant cultivars where available, use of pathogen-free tissue-cultured plants, strict quarantine and sanitation, biological control agents (e.g., *Trichoderma* spp.), soil amendments (organic matter, silicon), and cultural practices to reduce inoculum pressure. Chemical control is largely ineffective against a vascular soilborne pathogen in the field. Newer strategies include breeding (conventional and molecular) and gene editing (CRISPR/Cas-mediated) aimed at durable resistance (Blomme *et al.*, 2024; Tripathi *et al.*, 2020; Tripathi *et al.*, 2024).

Control measures for the management of TR4:

i. Crop rotation with cassava (*Manihot esculenta*) or garlic chives (*Allium tuberosum*)
ii. Soil suppression using bioorganic fertilizer that alter the microflora of soil
iii. In case of infected farms, farm machinery and tools should be thoroughly disinfected to prevent spread.
iv. Wherever possible, movement of people, machinery, tools, planting material and animals between fields should be minimized.
v. Host Resistance: Extensive research is going on TR4-resistant banana varieties, and many cultivated bananas have been screened for resistance to TR4, as well as wild species, such as *Musa* basjoo and *M. itinerans* are important for banana breeding programmes. In Taiwan, varieties called giant cavendish tissue culture variants, which have intermediate resistance to TR4 are being grown (Diksha Sinha, 2022).

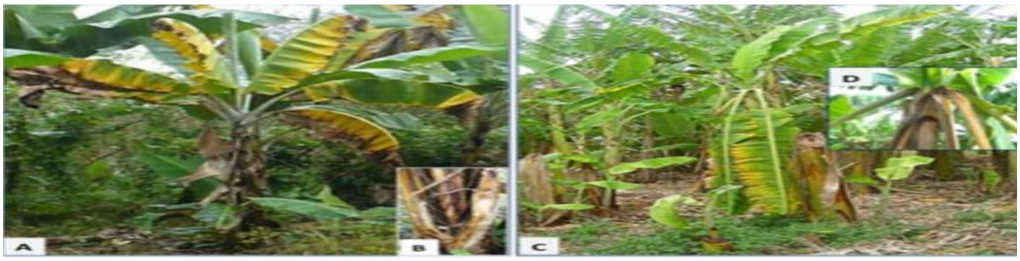

Figure 1: External symptoms of Fusarium wilt. A. Plant showing general yellowing and necrosis of leaves (yellow leaf syndrome´) in an advance state of disease. B. Pseudostem splitting. C. Plant affected by Fusarium wilt with green leaves (´green leaves syndrome´). D. Details of leaves fall down by the petiole collapse (cortesy: L. Pérez-Vicente and M. A. Dita; adapted from Dita *et al.*, 2013).

Figure 2: Internal symptoms of Fusarium wilt in banana. A. Transversal section of rhizome showing tissue necrosis. B. Transversal cut of pseudostem showing an advanced necrosis of vascular tissues. C. Longitudinal cut of pseudostem showing necrosis of the vascular strands (courtesy: M. A. Dita and L. Pérez-Vicente, adapted from Dita *et al.*, 2013).

2.2 Sigatoka leaf spot complex (Yellow and black sigatoka):

Causal agents: Yellow Sigatoka is caused by Mycosphaerella musicola (syn. Pseudocercospora *Musa*e), while Black Sigatoka (black leaf streak) is caused by Pseudocercospora fijiensis. Black Sigatoka is generally considered more aggressive and economically damaging (Noar *et al.*, 2022; Soares *et al.*, 2021).

Symptoms and impact: The presence of yellow sigatoka disease initially appears as small yellow spots on the leave of banana plants, as the disease advances, the size of yellow spots increase and may eventually come together to form a larger lesion (Calou *et al.,* 2020). Initial linear streaks on leaves develop into necrotic lesions; severe infection reduces photosynthetic leaf area, accelerates senescence, and lowers yield and fruit quality. The disease drives intensive fungicide use in commercial plantations and is sensitive to climatic variables like warmer, wetter conditions favor epidemics (Noar *et al.*, 2022; Bebber *et al.,* 2019).

Symptoms of black sigatoka: Initially the small dark spots appear on the lower leaves of banana plant, as the disease advances, these spot enlarge and trn in the irregularly shaped lesions that are dark brown to black in color. The existance of black leaf spotting affects banana yield, firstly it impairs the photosynthetic halt of leaves and decreases the leaf area thereby significantly impact on the weight of bunches. Secondly it reduced the duration of green life cycle (Saranya N, *et al.* 2020).

Management: Integrated control combines cultivar selection (tolerant lines), sanitation (removal of infected leaves), canopy management to reduce humidity, timely fungicide programs (careful rotation to avoid resistance), and biocontrol induced resistance research. Modeling studies and remote sensing are improving prediction and targeted spray scheduling (Soares *et al.*2021).

Figure 3: A Yellow Sigatoga, B Black Sigatoga

(Courtesy: Jadhaw and Bhandari, 2024)

2.3 Crown rot and post-harvest rots (Anthracnose):

Causal complex and symptoms: Post-harvest crown rot and anthracnose are caused by a complex of fungi — prominently Colletotrichum *Musa*e, Fusarium spp., and Lasiodiplodia theobromae. Symptoms emerge around harvest and during transport: crown tissue browning, softening, premature ripening and black rot on the peel and pulp, reducing shelf life and marketability (Lassois *et al.,* 2010; Krauss *et al.,* 2000; Finlay, 1993).

Management: Pre-harvest practices to minimize crown damage, careful handling, hot-water or post-harvest fungicidal dips, packaging hygiene, and the use of anti-microbial coatings or biocontrol agents can reduce incidence. Research emphasizes an integrated pre- and postharvest approach rather than sole reliance on postharvest fungicides (Lassois *et al.,* 2010; Krauss *et al.,* 2000).

Figure 4: Anthracnose symptoms (Courtesy: Arunkumar and Suthin Raj, 2021)

3. Major bacterial diseases:

3.1 Moko disease and ralstonia-associated wilt:

Etiology & symptoms: Moko disease is caused by Ralstonia solanacearum (various sequevars) and results in vascular wilt, yellowing, and bacterial ooze; it can also cause fruit rot. Ralstonia species within the *Ralstonia solanacearum* species complex (RSSC) infect many hosts and are highly adaptable (Soares *et al.,* 2021).

Epidemiology and management: Spread is via contaminated tools, irrigation water, infected planting materials, and soil movement. Management focuses on sanitation, use of clean material, crop-free periods, and integrated measures; breeding and biotechnological approaches are being explored (Blomme *et al.,* 2017; Soares *et al.,* 2021).

Figure 5: Various symptoms of Moko (A)/Bugtok (B) bacterial wilt caused by R. *solanacearum*. The photos depict (for A) premature fruit ripening and fruit discoloration, initial leaf symptoms on a sucker, and pseudostem discoloration; (for B) discoloration of fruit pulp and bunch stalk/rachis. Photos were taken in Colombia, Suriname, and Costa Rica (for Moko) and The Philippines (for Bugtok) by, respectively, Miguel Dita, Luis Pérez Vicente, and Philippe Prior. (Courtesy: Guy Blomme *et al.,* 2017)

3.2 Banana Xanthomonas Wilt (BXW):

Etiology and symptoms: Banana Xanthomonas Wilt BXW is caused by *Xanthomonas campestris pv. Musacearum* (Xcm). Symptoms include yellowing, wilting, bacterial ooze, and premature fruit ripening with internal discoloration. BXW has caused severe losses in East and Central Africa and remains a high-priority disease for smallholders (Nakato *et al.,* 2017).

Management: The toolbox includes early detection and removal (roguing) of infected plants, tool disinfection, cultural practices (sanitary harvesting, male bud removal), use of clean planting material, and community-based surveillance. Research into host resistance and transgenic approaches (e.g., expression of defense genes) shows promise in controlled settings (Nakato *et al.,* 2017; Blomme *et al.,* 2017).

Figure 6: Xanthomonas bacterial wilt caused by X. campestris pv. *Musa cearum*. The photos depict leaf yellowing and wilting, and pockets of bacterial ooze in a leaf petiole. Photos were taken in Ethiopia by Guy Blomme (Courtesy: Guy Blomme *et al.,* 2017)

4. Major viral diseases:

4.1 Banana Bunchy Top Virus (BBTV):

Causal agent & vector. Banana bunchy top disease is caused by Banana bunchy top virus (BBTV; family Nanoviridae) and is transmitted persistently by the banana aphid Pentalonia nigronervosa (Retkute *et al.*2025).

Symptoms and impact: Infected plants exhibit stunted growth, dark chlorotic streaks on petioles, and the characteristic 'bunchy top' of erect, clustered leaves. BBTV can cause near-total losses in affected fields (Retkute *et al.,* 2025; Jekayinoluwa *et al.,* 2020).

Management and control research: Control relies on vector control, eradication of infected plants, and provision of virus-free planting material. Biotechnological strategies, including RNAi and genetic engineering, are under investigation to confer resistance or to target the vector. Early detection using molecular assays and surveillance is essential to contain outbreaks (Jekayinoluwa *et al.*, 2020).

Figure 7: A: Leaf abnormilities in BBTV affected plant,
B: Suckers after mother plant infected with BBTV (Courtesy: Nelson, 2004)

4.2 Banana Streak Virus (BSV):

Overview and management challenges: BSV (genus Badnavirus, family Caulimoviridae) is complicated by the presence of endogenous BSV sequences in some banana genomes; stress can activate these sequences to produce virus particles. Management emphasizes the use of virus-free planting material and avoidance of stressors that may activate integrated sequences (Jekayinoluwa *et al.,* 2020).

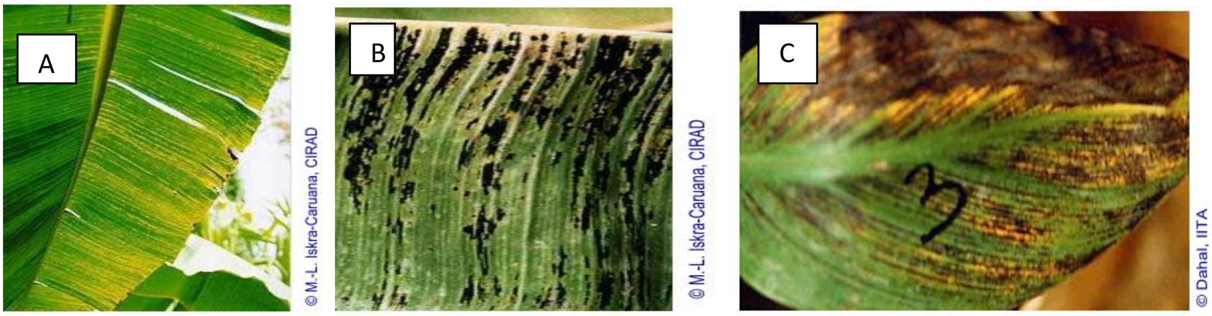

Figure 8: A, B: Typical streak B: Necrosis (Courtesy *et al.,* 2005)

5. Nematode pests:

Nematodes are small, worm-like members of the animal kingdom from 0.5-1.0 mm in length. They are found in, in fresh or salt water, and in soil. Most feed on other microscopic organisms, but some are animal and human, plant parasites. several hundred species attack plants. Plant-parasitic nematodes have stylets, spear-like mouthparts that pierce cells and allow them to feed on their contents (Fred Brooks, 2004),

The burrowing nematode *Radopholus similis* is the most important nematode in banana, causing root lesions, reduced root function, toppling disease, and significant yield losses if unmanaged. Other nematode genera (**e**.g., Pratylenchus, Meloidogyne, Helicotylenchus**)** also contribute to root decline (Sousa *et al.,* 2024; Haegeman *et al.,* 2010). Control strategies comprise hot-water treatment of planting material, nematicides (where permitted), organic amendments, resistant/tolerant germplasm, and biocontrol approaches; biotechnology (e.g., RNAi-based strategies and transgenics) is emerging as an option for durable management (Mwaka *et al.,* 2023; Dochez *et al.,* 2006).

Figure 9: A: Roots of plant invaded by brrowing nematode,
B: Reddish-black necrosis of root cortex caused by R. similis.,
C: Typical plant nematode (Courtesy: Fred Brooks, 2004)

6. Diagnostics, surveillance, and modeling:

Advances in diagnostics: from conventional isolation to PCR/qPCR, loop-mediated isothermal amplification (LAMP), and high-throughput sequencing — have improved detection speed and sensitivity. Remote sensing and machine learning models are increasingly used for field-scale disease surveillance (e.g., Sigatoka severity mapping, TR4 detection risk mapping, BBTV spread modeling), enabling targeted interventions and early warning systems. These tools complement traditional surveillance and community reporting systems (Thiagarajan *et al.,* 2024; Retkute *et al.,* 2025).

7. Integrated Disease Management (IDM):

Sustainable management of banana diseases requires integrated strategies tailored to pathogen biology and local contexts. Core IDM elements include:

Pathogen-free planting material: Tissue culture propagation and strict seed systems reduce initial inoculum and seed degeneration (Hasnain *et al.*2022; Jacobsen *et al.,* 2019).

Sanitation & quarantine: Disinfection of tools, control of movement of infected plant material, and farm hygiene reduce spread of soilborne and bacterial pathogens (Jacobsen *et al.*, 2019; Blomme *et al.*, 2017).

Host resistance and breeding: Conventional breeding, marker-assisted selection, and modern genome editing (CRISPR/Cas) are being used to develop varieties with resistance to Foc, BXW, and other major threats (Tripathi *et al.*2020; Tripathi *et al.*2024).

Biological control and microbiome management: Beneficial microbes (e.g. *Trichoderma, Bacillus, Pseudomonas*) and endophyte priming can suppress Foc and other pathogens, improve plant vigor, and reduce reliance on chemical pesticides. Microbial consortia are increasingly evaluated for better and more consistent control (Solórzano *et al.,* 2025; Long *et al.,* 2023; Yao *et al.,* 2023).

Cultural practices and soil health: Crop rotation (where feasible), organic amendments, silicon fertilization, and balanced nutrition enhance plant resilience (Blomme *et al.*, 2024; Jackson *et al.*, 2024).

Chemical control: Fungicides and bactericides have targeted roles (postharvest rots, Sigatoka sprays) but must be used judiciously to avoid resistance development and environmental/human health impacts (Noar *et al.*, 2022; Soares *et al.*, 2021).

Community engagement: In smallholder systems, farmer training and community-wide coordinated actions (e.g., for BXW containment) are essential (Blomme *et al.*, 2017; Nakato *et al.*, 2017).

8. Biotechnological advances and prospects:

Biotechnological interventions are among the most active research areas for banana disease management.

i. Tissue culture and pathogen-free nurseries provide clean planting material though seed degeneration in the field remains a challenge if planting into infested soils (Hasnain *et al.*, 2022).
ii. Transgenics & RNAi: Expression of defense-related genes and RNAi targeting of pathogens or vectors has shown partial resistance in trials (e.g., transgenic lines for BXW or nematode resistance); regulatory, acceptance, and IP issues remain barriers to deployment in many regions (Jekayinoluwa *et al.,* 2020; Mwaka *et al.,* 2023).
iii. Genome editing (CRISPR/Cas): CRISPR-mediated editing is rapidly maturing for banana and offers a faster route to targeted, non-transgenic changes (depending on regulatory frameworks) for traits including disease resistance and desirable agronomic traits. Protocol optimization and delivery methods are active research areas (Tripathi *et al.,* 2020; Tripathi *et al.,* 2024).
iv. Microbiome engineering & consortia: Harnessing beneficial microbial communities for disease suppression and plant growth promotion is promising, with recent meta-analyses favoring multi-strain consortia over single-strain inoculants (Solórzano *et al.,* 2025).

9. Socioeconomic considerations and implementation challenges:

Implementing IDM and modern tools is context-dependent. Smallholder farmers often lack access to certified planting material, diagnostics, or extension services; economic constraints limit uptake of intensive fungicide programs or new cultivars. Policy, extension, and market incentives are required to scale up clean-plant systems, community surveillance, and adoption of resistant/tolerant germplasm. International collaboration and biosecurity measures are central to limiting transboundary pathogen spread (e.g., TR4) (Blomme *et al.,* 2017; Blomme *et al.,* 2024).

10. Research Gaps and Future Directions:

Key research priorities include:

i. Durable resistance sources and rapid breeding pipelines (including precision breeding/CRISPR) (Tripathi *et al.*, 2020; Tripathi *et al.*, 2024).

ii. Scalable, affordable diagnostics for in-field detection of TR4, BBTV, Xcm, and other priority pathogens (Thiagarajan *et al.*, 2024; Retkute *et al.*, 2025).
iii. Microbial consortia optimization and formulation for consistent field performance across environments (Solórzano *et al.*, 2025).
iv. Socioeconomic research on adoption barriers and design of extension programs tailored to smallholders (Blomme *et al.*, 2014; Jacobsen *et al.*, 2019).
v. Improved vigilance and surveillance networksare essential using remote sensing, machine learning, and community reporting to enable early response (Retkute *et al.*, 2025; Thiagarajan *et al.*, 2024).

Conclusion:

Banana production faces significant and evolving disease threats across the globe. An integrated approach combining clean planting material, sanitation, cultural practices, biological control, precision fungicide use, resistant germplasm development, and modern biotechnologies offers the most realistic route to sustainable disease management. Effective implementation demands coordinated research-to-farmer pathways, policy support, and international collaboration to prevent pathogen spread and support livelihoods dependent on banana production.

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GREEN SYNTHESIS OF SILVER NANOPARTICLES: A SUSTAINABLE APPROACH OVER CONVENTIONAL METHODS

Sunidhi, Rajender Kumar Gupta* and Rishu

CCS Haryana Agricultural University, Hisar

*Corresponding author E-mail: gupta_raj123@yahoo.com

Introduction:

Nanotechnology is an immensely popular and rapidly growing field due to its ability to address global challenges with innovative and cost-effective solutions. Nanotechnology modifies materials to nanosizes ranging from approximately 1 to 100 nm, changing the particle size, surface area, surface reactivity, charge and shape and these nanoparticles serve as the fundamental blocks of nanotechnology. The reduced size, modified properties and intriguing features of nanoparticles make them suitable for applications in industrial, commercial and biological fields (Srikar *et al.*, 2016). Nanoparticles are primarily classified by their composition (e.g., metallic, polymeric, ceramic), shape, and surface chemistry. Nanoparticles of noble metals, including platinum, titanium, gold, and silver, are frequently employed in nanomedicine. Common examples include gold nanoparticles used in medical diagnostics, titanium dioxide nanoparticles in sunscreens, and carbon nanotubes in electronics. However, their use also introduces important questions regarding synthesis, stability, environmental persistence, toxicity, and regulatory oversight.

Silver nanoparticles (AgNPs), pioneers in nanotechnology, are used in various applications, including drug delivery, ointments, nanomedicine, chemical sensing, data storage, cell biology, agriculture, textiles, the food industry, photocatalytic organic dye–degradation activity, antioxidants, and antimicrobial agents. Specifically, the silver nanoparticle has attracted immense attention due to its exceptional qualities, including chemical stability, high conductivity, catalytic activity, etc. (Ahmed *et al.*, 2015). Their small size allows them to penetrate deep into tissues, making them effective in various applications. Various chemical, physical, and biological methods can be employed to produce silver nanoparticles (AgNPs); however, biological approaches demonstrate notable cost-effectiveness, non-toxicity, and environmental friendliness in the production of Ag-NPs as natural reducing agents replaces harsh chemicals (Abalkhil *et al.*, 2017). The plant based synthesis of silver nanoparticles is also suitable for biomedical applications.

Classification of nanoparticles:

The nanoparticles exhibit varying shapes, sizes, and structures. It can be spherical, cylindrical, tubular, conical, hollow core, spiral, flat, or irregular, varying in size from 1 nm to

100 nm. Surface variations may result in a uniform or irregular surface. Some nanoparticles have single or multiple crystal solids that are either loose or clumped together, and they can be crystalline or amorphous (Machado *et al.*, 2015).

Nanoparticles are typically categorised into three classes based on their composition: organic, carbon-based, and inorganic (Ealia and Saravanakumar, 2017).

Organic nanoparticles:

This class includes NPs composed of proteins, carbohydrates, lipids, polymers, or other organic compounds (Pan and Zhong, 2016). Prominent examples of this class include dendrimers, liposomes, micelles, and protein complexes like ferritin. These nanoparticles are generally non-toxic, biodegradable, and may possess a hollow core in certain instances, such as with liposomes. Organic nanoparticles exhibit sensitivity to thermal and electromagnetic radiation, including heat and light (Ealia and Saravanakumar, 2017). Moreover, they are frequently established through non-covalent intermolecular interactions, resulting in increased lability and facilitating clearance from the body. Various parameters influence the potential applications of organic nanoparticles, including composition, surface morphology, stability, and carrying capacity (Joudeh and Linke, 2022). Currently, organic nanoparticles are primarily utilised in the biomedical sector for targeted drug delivery and cancer treatment (Razavi *et al.*, 2025).

Carbon-based nanoparticles:

This class consists of NPs composed exclusively of carbon atoms. Notable instances of this category include fullerenes, carbon black nanoparticles, and carbon quantum dots. Fullerenes are carbon molecules distinguished by a symmetrical, closed-cage architecture. Fullerenes (C_{60}) are spherical carbon molecules composed of carbon atoms interconnected through sp^2 hybridisation. Carbon black nanoparticle is an amorphous substance composed of carbon, typically exhibiting a spherical form, the strong interactions among the particles result in the formation of agglomerates around 500 nm in size (Ealia and Saravanakumar, 2017). Carbon quantum dots are discrete, quasi-spherical carbon nanoparticles with dimensions under 10 nm (Lu *et al.*, 2016) Owing to their distinctive electrical conductivity, exceptional strength, electron affinity, and optical, thermal, and sorption characteristics, carbon-based nanoparticles are employed in diverse applications including drug delivery, energy storage, bioimaging, photovoltaic devices, and environmental sensing for monitoring microbial ecology or detecting microbial pathogens (Joudeh and Linke, 2022).

Inorganic nanoparticles:

Nanoparticles composed of metals and metal oxides are often classified as inorganic nanoparticles. This creates them progressively vital materials for the advancement of nanodevices applicable in various physical, chemical, biological, biomedical, and pharmacological domains (Mody *et al.*, 2010). Inorganic nanoparticles offer versatility and potential for various industrial and biomedical applications. Metal-based nanoparticles are created by synthesising metals to nanometric sizes using either constructive or destructive techniques. It is possible to synthesise the nanoparticles of almost every metal. The metals aluminium, cadmium, cobalt, copper, gold, iron, lead, silver, and zinc are frequently utilised in the synthesis of nanoparticles. In order to alter the characteristics of their respective metal-based nanoparticles, metal oxide-based nanoparticles are synthesised. For instance, iron nanoparticles at room temperature instantly oxidise to iron oxide (Fe_2O_3) when exposed to oxygen, increasing their reactivity in comparison to iron nanoparticles. The primary reason for the manufacture of metal oxide nanoparticles is their enhanced efficiency and reactivity (Ealia and Saravanakumar, 2017). Numerous inorganic nanomaterials have been developed with superior performance, which has resulted in their exceptional clinical applications and translations in the field of therapeutic agents. These agents include antitumor therapy, iron-replacement therapy, antibacterial agents, bone graft substitutes, and antidotes for heavy metal poisoning (Huang *et al.*, 2020).

Silver nanoparticles:

Silver is a transition metal that is known for its excellent conductivity, malleability, and exquisite shine. Silver is still one of the most expensive and useful metals. It may be used for a wide range of items, from old coins and jewellery to cutting-edge uses in electronics and medicine. It even outperforms copper and gold as the finest natural conductor of heat and electricity among all metals. Compared to a number of other transition metals, silver has a lower chemical reactivity. Silver nanoparticles have much better physicochemical properties than bulk silver, which are attributed to their altered crystallite sizes and patterns. The usual size range of silver nanoparticles is 1–100 nm. Because of their special optical, electrical, and antibacterial qualities, silver nanoparticles (AgNPs) are widely used in a variety of fields, such as biosensing, photonics, electronics, and antimicrobial therapies.

Methods of synthesis:

In recent decades, there has been a great deal of interest in a variety of synthesis processes and their diverse range of uses. AgNPs may now be synthesised using chemical, physical, photochemical, and biological procedures. Every technique has pros and cons, and frequent issues include size distribution, cost, scalability, and particle size. High temperatures, vacuum conditions, and costly equipment are frequently needed for physical and photochemical processes. Due to their ease of use and effectiveness, chemical techniques are the most popular among them for producing AgNPs. These techniques work effectively for creating clean, distinct nanoparticles in simple, moderate environments. Silver ions are usually reduced in water or organic solvents to create colloidal dispersions with different particle sizes in chemical synthesis

(Sati *et al.*, 2025). The growing need for metallic nanoparticles in environmental and biomedical applications is being answered by recent advancements in the environmentally friendly synthesis of AgNPs, which offers a cost-effective, efficient, and sustainable substitute for traditional techniques.

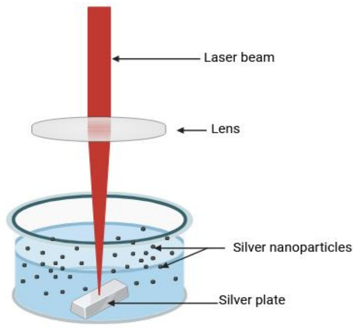
Two main methods are used in the manufacture of silver nanoparticles: the "top to bottom" method and the "bottom to up" method. The top-to-bottom process uses a variety of lithographic methods, including sputtering, grinding, milling, and thermal or laser ablation, where a suitable bulk material is reduced in size to produce small particles. This method's drawbacks include the need for a lot of room, energy, temperature, and time in order to achieve thermal stability. In contrast, chemical and biological techniques are used in the bottom-to-top strategy to create nanoparticles through the self-assembly of atoms to create new nuclei that develop into tiny particles (Ahmed *et al.*, 2015)

An overview of the physical, chemical, and green synthesis methods used to synthesise silver nanoparticles is given in this chapter.

1. Synthesis using physical methods:

Physical techniques, which are typically classified as "top-down" processes, use an enormous amount of energy to break down bulk silver material into particles of nano-scale size. Although these methods frequently require a large energy input and specialized equipment, they are highly prized for their capacity to manufacture high-purity AgNPs without the need of chemical reducing agents or stabilizers. Evaporation-condensation and Laser Ablation in Liquid are the two widely used physical techniques along with mechanical mlling where bulk silver is milled into nanoparticles and sputtering technique.

Laser ablation synthesis in solution



Laser ablation in solution

Using laser ablation, 99.95% pure silver is synthesized into nanoparticles in an aqueous medium at 1064 nm, 50 mj, and 7 ns. An explosion occurs in the vicinity of silver when a laser is fired there due to a sudden increase in temperature. The laser shot causes silver particles to peel, generating particles that are released during the explosion. A high heat bubble is created by the explosion; the bubble disappears as it receives low temperature and high pressure from the medium's normal condition. The residual redispersed nano-size silver particles scatter uniformly throughout the liquid as a result of the bubbles dissipating (Elashmawi and Menazea, 2022)

Irradiation method

An established and potent approach for creating AgNPs through radiolysis is the irradiation method, which mostly uses electron beams or gamma (γ) rays to form consistent or uniform nanoparticles of controlled size and radiation can sterilize nanoparticles for biomedical applications. Because irradiation method of AgNPs synthesis uses the ionization of the solvent (usually water) to produce highly reactive reducing species like the hydrated electron and hydrogen radical, which directly convert Ag^+ ions to neutral Ag^0 atoms before nucleation and growth, this process is regarded as a clean substitute for traditional chemical reduction (Mossa and Shameli, 2021).

Evaporation- condensation technique

This process uses thermal evaporation of a silver source, usually in a tube furnace or by a local heater. The silver vapour is then transported by an inert gas into a cool area where it condenses as AgNPs. Increasing the gas pressure and applied inert gas mass results in nanoparticles with a larger average particle size. The rate of evaporation controls the formation of atom clusters. The evaporation-condensation process enhances the material's purity by eliminating volatile contaminants (Nguyen *et al.*, 2023).

Advantages and disadvantages of physical methods

Advantages	Disadvantages
Yields chemically pure AgNPs devoid of stabilizing agents or chemical contaminants.	Poor scalability and low production yield for industrial use.
By modifying the laser's parameters such as wavelength and pulse duration, particle size and shape can be precisely controlled.	Absence of stabilizing chemicals may cause particles to aggregate over time.
Eliminates the need for hazardous chemicals allowing the use of pure solvents, such as water.	High energy input, extended processing time and costly equipment are required.

2. Synthesis using chemical methods:

Because of their ease of use, affordability, and high yield, chemical synthesis techniques are the most used ways for creating AgNPs. This method offers high yield i.e. large quantities of nanoparticles can be produced. These approaches fall under the "bottom-up" category, including the assembly of nanoparticles from atomic or molecule precursors in solution. When silver atoms (Ag^0) are reduced from a silver salt precursor (usually silver nitrate, $AgNO_3$), they nucleate and develop into nanoparticles. Sol-gel, microemulsion, and chemical reduction are key techniques.

Chemical reduction

The most common and scalable technique for creating AgNPs in solution is chemical reduction. Silver ions (Ag^+) are converted into neutral silver atoms (Ag^0) by a reducing agent. In order to manage particle size and avoid agglomeration, a stabilizing/capping agent like polyvinylpyrrolidone (PVP), trisodium citrate or surfactants is necessary. It demands the use of potentially hazardous stabilizing and reducing chemicals, which can limit biomedical applicability and stay as surface pollutants (Nguyen *et al.*, 2023).

Sol Gel technique

AgNPs are created via the sol-gel process by embedding them in a solid porous matrix, like metal oxide or silica. A sol (colloidal suspension) is the initial state of the process, which develops into a gel (solid network). In this matrix, the silver precursor is reduced in situ, frequently using heat or a reductant. By inhibiting particle aggregation and enabling precise control over the homogeneity and size (5–50 nm) of the extremely stable AgNPs, the matrix acts as an effective stabilizer (Morales *et al.*, 2009).

Microemulsion technique

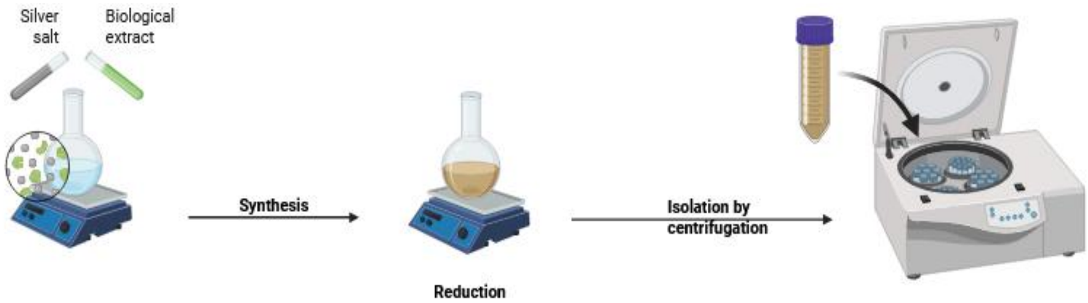
The microemulsion approach is a potent way to create extremely monodisperse AgNPs with remarkable control over size (usually between 2 and 10 nm). The fundamental process is stabilizing a thermodynamically stable mixture (microemulsion) with a surfactant, creating micelle droplets, which are tiny droplets that function as nanoreactors. Mixing distinct micelle solutions containing the silver precursor and reducing agent ($NaBH_4$, hydrazine, etc.) restricts the AgNP production reaction to these droplets. The micelle size, which can be readily adjusted by altering the water-to-surfactant molar ratio (W/S), directly controls the ultimate particle size (Nguyen *et al.*, 2013).

Advantages and disadvantages of chemical methods

Advantages	Disadvantages
Chemical reduction technique involves low equipment cost, simplicity, and scalability.	Low monodispersity due to poor size control
Sol gel method develops hybrid materials for optical and catalytic applications, such as thin films.	Film cracking can be caused by a protracted procedure, expensive precursors, and sensitivity to environmental conditions.
Microemulsion technique gives excellent control over size; produces NPs that are largely monodisperse.	Expensive (high surfactant/solvent usage); challenging to purify

3. Biological (Green) synthesis

Silver nanoparticles (AgNPs) can be produced on a sustainable basis using biological synthesis, also known as "Green Synthesis," which uses biological agents as bacteria, fungi, yeast, algae, or plant extracts. By using the biomolecules (such as proteins, enzymes, and polyphenols) found in biological agents as both stabilizing and reducing agents, this technique avoids the hazardous chemicals and high energy inputs associated with conventional chemical and physical procedures.



Biological synthesis of silver nanoparticles

Synthesis using microorganisms:

Utilizing the reducing ability of bacteria, fungus, algae, or yeast to transform silver ions (Ag^+) into elemental silver (Ag^0) nanoparticles, the microorganism-mediated green production of silver nanoparticles (AgNPs) has become a fundamental green technology (Mustapha *et al.*, 2022). Three steps are typically involved in synthesis of silver nanoparticles (AgNPs) using microorganisms:

- *Biomass preparation*: First, the chosen microorganism (such as fungus like *Fusarium oxysporum* or bacteria like *Bacillus subtilis*) is cultivated in a suitable nutritional broth. The culture is spun for a preferred extracellular production, and the cell-free supernatant which includes important biomolecules like enzymes and co-enzymes is separated to serve as the main reducing agent (Kalishwaralal *et al.*, 2008).
- *Nanoparticle synthesis*: The cell-free supernatant is mixed with an aqueous solution of Silver Nitrate ($AgNO_3$) and the mixture is incubated frequently with shaking, at room temperature or slightly above it. The reduction of silver ions (Ag^+) to silver atoms (Ag^0), which subsequently nucleate and develop into AgNPs, the reaction is catalyzed by the reducing agents in the supernatant during this incubation (Pandey, 2025). The Surface Plasmon Resonance (SPR) phenomenon causes a color shift to yellow or brown, which visibly confirms the successful creation of AgNPs (Mustapha *et al.*, 2022).
- *Purification and Characterization*: High-speed centrifugation is used to separate the AgNPs, which are then washed to get rid of organic residues and unreacted silver. Following that, the final NPs are examined using FTIR to determine the stabilizing protein/metabolite capping agents, TEM/SEM for size and shape, and UV-Vis spectroscopy for SPR confirmation (Thirumurugan *et al.*, 2024).

Synthesis using plants

Plant-mediated green synthesis of silver nanoparticles (AgNPs) has drawn a lot of interest as a simple and environmentally friendly substitute for traditional techniques, largely because it is inexpensive and non-toxic. The biomolecules found naturally in the plant extract—such as proteins, enzymes, and secondary metabolites like phenolics and terpenoids act as both reducing and stabilizing agents in this method, which has the clear advantage of removing the need for external, frequently hazardous chemical stabilizers and streamlining the entire procedure for possible large-scale synthesis (Rajeshkumar and Bharath, 2017). Various biological techniques are being investigated for the synthesis of metallic nanoparticles in a range of sizes and shapes from different plant components, including leaves, stems, roots, seeds, fruit, calluses, peels, and flowers. Prasad and Elumalai (2011) used a 1 mM AgNO3 solution and leaf extract from *Moringa oleifera* to create silver nanoparticles with a diameter of 57 nm. According to Singhal *et al.* (2011), crystalline AgNPs (4–30 nm) were created in 8 minutes using an extract from *Ocimum sanctum* leaves. They discovered that the ascorbic acid in *O. sanctum* leaves helped to reduce silver ions and proteins served as capping agents to increase the stability of the ions.

Methodology of plant mediated biosynthesis of silver nanoparticles

The following methodology is used to create plant-mediated silver nanoparticles, while process optimization is crucial depending on the type of plant, the required NP size, and other factors.

1. *Prepration of plant extract*: The desired plant part (e.g. fruit, leaves) is collected, examined for disease or infection, and powdered after through washing with distilled water. To assure the homogeneity of the plant extract solution, the plant material is boiled in water at 60 °C in a water bath to create an extract rich in phytochemicals like phenolics, flavonoids, and terpenoids, which are the active reducing agents.
2. *Nanoparticle formation*: The prepared extract is mixed in silver salt ($AgNO_3$) solution while stirring at ambient temperature. The change in color from light yellow to brown confirms the reduction of pure Ag(I) ions to Ag(0). It can be tracked by periodically measuring the solution's UV–visible spectra. Isolation takes place as the formed AgNPs undergo repeated cycles of centrifugation and washing with deionized water to remove them from the reaction media.
3. *Characterization of nanoparticles*: After drying the purified NPs in hot air oven, stable silver nanoparticles powder is obtained that is characterized using various techniques like TEM/SEM to examine the size, shape, and morphology; XRD to ascertain crystallinity; and UV-Vis Spectroscopy to validate the SPR peak (about 400–450 nm). The capping biomolecules that give nanoparticle stability are identified using FTIR (Sharma and Kumar, 2021).

Green synthesis over conventional methods:

By addressing the two main disadvantages of traditional physical and chemical methods- toxicity and excessive energy consumption; green synthesis of silver nanoparticles (AgNPs) has become a superior, sustainable alternative. Despite their high yield and quick synthesis, traditional chemical reduction techniques commonly employ toxic stabilizing agents and hazardous reducing agents (such as sodium borohydride or hydrazine), which pollute the environment and reduce the final product's biological suitability for applications in biomedical sciences (Sati *et al.*, 2025). Physical techniques like evaporation-condensation and laser ablation also require a lot of energy, pressure, or complicated equipment, which makes large-scale production slow and expensive (Iravani *et al.*, 2014).

The use of natural, non-toxic substances such as fungi, bacteria, algae, or plant extracts (including polyphenols, terpenoids, etc.) in green synthesis, on the other hand, serves as both the reducing and capping/stabilizing agent. This method is usually easy, inexpensive, and safe for the environment because it is usually a one-step process carried out under mild ambient conditions like low temperature and pressure, thus lowering energy costs and the production of hazardous waste (Asif *et al.*, 2022). Furthermore, because the surface coating of natural biomolecules on the resulting green-synthesized AgNPs can improve their stability, drug-targeting capability, and superior biological activity such as improved antibacterial efficacy against drug-resistant strains as they are often more biocompatible and therefore highly desirable for use in pharmaceutical and industrial settings (Habeeb Rahuma *et al.*, 2022).

Conclusion:

The green synthesis of silver nanoparticles (AgNPs) is a significant and sustainable advancement over traditional techniques. Physical and chemical processes are frequently quick, but they use a lot of energy, produce hazardous byproducts, and depend on dangerous reagents. By using natural extracts (from plants or microbes), the green approach completely avoids these problems and offers an affordable, environmentally responsible, and simplistic platform.

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PHYSIOTHERAPY INTERVENTIONS FOR AGRICULTURAL INJURY REHABILITATION: EVIDENCE-BASED APPROACHES

Pooja Katiyar[1] and Sanhita Sengupta*[2]

[1]Teerthanker Mahaveer University, Moradabaad, Uttar Pradesh, 244102

[2]Brainware University, Kolkata, West Bengal, 700125

*Corresponding author E-mail: sas.ah@brainwareuniversity.ac.in

Abstract:

Agricultural workers experience disproportionately high rates of work-related musculoskeletal disorders (WMSDs), with lifetime prevalence reaching 90.6% and annual prevalence of 76.9%. Low back pain represents the most common complaint, resulting from repetitive movements, prolonged awkward postures, heavy lifting, and sustained stooping during farming activities. These injuries occur over 20 times more frequently than pesticide injuries in agriculture, causing substantial economic losses and long-term disability. This chapter synthesizes current evidence on physiotherapy interventions for agricultural injury rehabilitation, examining assessment protocols, manual therapy techniques, therapeutic exercise programs, postural re-education, ergonomic modifications, pain management strategies, and patient education approaches. Evidence from systematic reviews demonstrates that multimodal interventions combining manual therapy, therapeutic exercise, and education produce clinically meaningful improvements in pain, function, and work capacity. Spinal manipulation and mobilization significantly reduce pain intensity and disability, while exercise therapy, particularly core stabilization and task-specific functional training consistently demonstrate superior outcomes for chronic low back pain management. Ergonomic workplace modifications and postural training reduce injury risk and facilitate sustainable return to work. Implementation requires individualized approaches considering specific biomechanical demands of different farming operations, seasonal work patterns, and psychosocial factors unique to agricultural communities. Service delivery faces challenges including geographic isolation, economic constraints, and limited specialized training among rehabilitation professionals. Emerging technologies such as telerehabilitation offer promising solutions to address access barriers. Future research should prioritize randomized controlled trials in agricultural populations, long-term outcome studies, and implementation strategies addressing rural healthcare delivery barriers to reduce the substantial burden of musculoskeletal disorders in this vital workforce.

Keywords: Agricultural Injuries, Musculoskeletal Disorders, Physiotherapy, Rehabilitation, Exercise Therapy, Manual Therapy, Ergonomics, Occupational Health, Low Back Pain, Farm Workers

Introduction:

Agricultural work represents one of the most physically demanding occupations globally, with workers facing unique biomechanical challenges that significantly impact musculoskeletal health. The agricultural sector employs nearly one-third of the world's workforce, and these workers experience disproportionately high rates of work-related musculoskeletal disorders (WMSDs) compared to other industries [1]. Agricultural workers face risk factors including repetitive movements, awkward postures, heavy lifting, whole-body vibration from machinery, and prolonged periods of stooping and squatting that contribute to chronic disability and reduced productivity [2].

Recent epidemiological data reveal alarming prevalence rates of musculoskeletal injuries among agricultural populations. Studies indicate that the estimated lifetime prevalence of musculoskeletal disorders among farmers reaches 90.6%, with one-year prevalence rates of 76.9% [3]. A systematic review examining musculoskeletal disorders among farmers found prevalence rates ranging from 20% to 90%, with low back pain being the most commonly reported condition [4]. In low- and middle-income countries, the burden is even more pronounced, with 12-month pooled prevalence of low back pain reaching 61.96% in Africa and 54.16% in Asia—figures substantially exceeding global population averages [5].

The impact of agricultural injuries extends beyond individual suffering to substantial economic consequences. Musculoskeletal disorders occur over 20 times more frequently than pesticide injuries in United States agriculture, costing the American farming industry in excess of $167 million for reported injuries alone [3]. Furthermore, agricultural workers face particular risk of arthritis-related disability, with musculoskeletal disorders causing long-term disability and significant income loss [6]. These statistics underscore the critical need for evidence-based physiotherapy interventions specifically tailored to the agricultural workforce.

Physical rehabilitation professionals, particularly physiotherapists, play a pivotal role in restoring agricultural producers' functional capacities and facilitating their return to farming activities. The unique demands of agricultural work characterized by seasonal variability, diverse physical tasks, and work environments requiring specialized knowledge, necessitate that physiotherapists possess specific competencies to effectively address the rehabilitation needs of workers with musculoskeletal disorders [7]. This chapter examines the evidence-based physiotherapy interventions for agricultural injury rehabilitation, with particular emphasis on musculoskeletal disorders that predominantly affect the lower back, shoulders, knees, neck, and upper extremities.

Description of physiotherapy interventions

Assessment and evaluation protocols

Comprehensive assessment forms the foundation of effective physiotherapy intervention for agricultural injuries. Physical rehabilitation professionals must conduct thorough evaluations that consider not only the presenting musculoskeletal complaint but also the specific agricultural work demands, ergonomic risk factors, and functional limitations that impact the worker's ability to perform essential farm tasks [8].

Standardized assessment tools widely utilized in evaluating agricultural workers include the Nordic Musculoskeletal Questionnaire (NMQ), which assesses symptom prevalence across different body regions, and the Rapid Entire Body Assessment (REBA) tool, which evaluates postural risk factors associated with specific agricultural tasks [9]. Additionally, functional outcome measures such as the Oswestry Disability Index (ODI) for low back pain and the Visual Analog Scale (VAS) for pain intensity provide quantifiable metrics to track rehabilitation progress and intervention effectiveness [10].

The evaluation process must extend beyond clinical measures to include occupational task analysis, where physiotherapists observe or simulate specific farming activities to identify biomechanical stressors. This contextualized assessment approach enables therapists to develop intervention strategies that directly address the functional demands of agricultural work [11]. Biomechanical factors most commonly associated with agricultural injuries include repetitive use of body parts, bending and twisting of the back, sustained awkward postures, and forceful exertions during lifting and carrying [2].

Manual therapy techniques

Manual therapy represents a cornerstone intervention in the physiotherapeutic management of agricultural injuries, particularly for chronic musculoskeletal pain conditions. Evidence from systematic reviews and meta-analyses demonstrates that manipulation and mobilization techniques produce clinically meaningful improvements in pain reduction and functional restoration for workers experiencing work-related injuries [10].

Spinal manipulation, characterized by high-velocity, low-amplitude thrust techniques, has demonstrated moderate-quality evidence for producing small to moderate reductions in pain intensity compared to other active interventions. A comprehensive meta-analysis found that manipulation interventions significantly reduced pain when compared to other active therapies [10]. The therapeutic effect appears to increase over time at three and six-month follow-up periods, suggesting sustained benefits particularly relevant for agricultural workers requiring long-term functional capacity.

Spinal mobilization techniques, involving gentle, repeated pressure along the spine and surrounding soft tissues, provide an alternative manual therapy approach particularly suitable for acute injuries or when high-velocity manipulation is contraindicated. While mobilization demonstrates more modest effects compared to manipulation, evidence indicates it significantly reduces pain intensity relative to control interventions [10]. For agricultural workers presenting with lower back pain—the most prevalent musculoskeletal complaint in farming populations, manual therapy combined with exercise yields superior outcomes compared to either intervention alone [12].

Soft tissue mobilization and massage therapy address the muscular components of agricultural injuries, which often involve overuse syndromes, muscle strains, and trigger point development from repetitive farm tasks. These techniques improve tissue extensibility, reduce muscle tension, enhance circulation, and modulate pain through neurophysiological mechanisms [13]. Clinical application of manual therapy must be individualized based on the specific injury presentation, chronicity, and the agricultural worker's tolerance and preferences.

Therapeutic exercise programs

Therapeutic exercise constitutes the most extensively researched physiotherapy intervention for agricultural injury rehabilitation, with robust evidence supporting its efficacy in reducing pain, improving function, and facilitating return to work. Exercise interventions must address restoration of mobility, improvement of strength, enhancement of neuromuscular control, increased cardiovascular endurance, and preparation for the specific physical demands of farming activities, with effectiveness demonstrated through systematic reviews showing clinically meaningful benefits for chronic low back pain [14].

Core strengthening and stabilization: Given the high prevalence of low back pain among agricultural workers, core strengthening exercises form a critical component of rehabilitation programs. Systematic reviews demonstrate that core stabilization exercises, which target the deep abdominal muscles (transversus abdominis) and lumbar multifidus, produce significant improvements in pain and disability for chronic low back pain. A Cochrane review analyzing 249 randomized controlled trials found that exercise therapy consistently demonstrated clinically meaningful benefits for chronic low back pain, with effect sizes indicating moderate improvements in pain and function [15].

Core stabilization programs typically progress through phases, beginning with isolated activation of deep stabilizers in neutral spine positions, advancing to integration during functional movements, and culminating in dynamic stabilization during task-specific activities that simulate agricultural work. For example, exercises might progress from supine drawing-in maneuvers to quadruped positions, standing balance challenges, and ultimately to maintaining core stability while lifting, twisting, and bending—movements frequently required in farming operations [16].

General strengthening exercises: Beyond core-specific training, general strengthening exercises targeting major muscle groups address the comprehensive physical demands of agricultural work. Progressive resistance training for the lower extremities (quadriceps, hamstrings, gluteal muscles) and upper extremities (shoulder girdle, rotator cuff, forearm muscles) builds the muscular capacity necessary to safely perform repetitive lifting, carrying, and overhead work common in farming [14]. Evidence indicates that strengthening programs should utilize progressive overload principles, gradually increasing resistance and complexity to optimize strength gains while minimizing injury risk during the recovery phase.

Stretching and flexibility training: Prolonged static postures and repetitive movements characteristic of agricultural work lead to adaptive shortening of muscles and connective tissues, contributing to movement restrictions and compensatory patterns. Systematic stretching programs addressing commonly tight muscle groups—hip flexors, hamstrings, thoracic spine extensors, pectorals, and cervical muscles help restore optimal length-tension relationships and improve movement quality [17]. Evidence supports both static and dynamic stretching approaches, with implementation timing dependent on treatment phase and individual response.

Aerobic conditioning: The physical demands of agricultural work require substantial cardiovascular endurance, making aerobic conditioning an essential component of comprehensive rehabilitation. Walking programs, cycling, swimming, and other forms of aerobic exercise improve cardiovascular fitness, enhance overall health status, and facilitate metabolic processes supporting tissue healing [15]. Research demonstrates that aerobic exercise contributes to pain modulation through multiple mechanisms, including endogenous opioid release, improved tissue oxygenation, and psychological benefits such as reduced anxiety and improved self-efficacy.

Task-specific functional training: The ultimate goal of rehabilitation involves preparing agricultural workers for safe return to farming activities. Task-specific functional training bridges the gap between clinical exercises and occupational demands by incorporating movements that simulate actual farm work. This approach aligns with motor learning principles emphasizing specificity of training and transfer of skills [18]. Functional training might include practicing proper lifting mechanics with progressively heavier loads, simulating reaching and overhead movements required for crop harvesting, or training balance and coordination needed for working on uneven terrain.

Postural re-education and body mechanics training

Agricultural work frequently involves prolonged periods in biomechanically disadvantaged postures stooping during weeding, sustained forward flexion while harvesting, overhead reaching during pruning, and repetitive trunk rotation during shoveling. These postural demands contribute significantly to the development and perpetuation of musculoskeletal disorders [19]. Postural re-education and body mechanics training aim to modify movement patterns, optimize biomechanical loading, and reduce injury risk during agricultural activities.

Evidence-based postural training begins with increasing workers' awareness of their habitual postures and movement patterns through education, mirror feedback, or video recording. Once awareness is established, physiotherapists guide workers in developing alternative movement strategies that distribute loads more evenly across body structures and minimize high-risk postures [20]. Proper lifting mechanics education remains fundamental for injury prevention in agricultural settings, with contemporary approaches emphasizing individualized lifting strategies that consider the worker's physical capacities, task demands, and environmental constraints.

For agricultural workers, postural modifications must be practical and sustainable within the farm environment. Recommendations might include alternating between kneeling and squatting positions during ground-level work, incorporating "reversal" strategies where workers periodically move into opposite positions to allow tissue recovery, and designing work stations at heights that minimize extreme forward bending [19]. Studies examining occupationally-oriented medical rehabilitation for farmers have demonstrated that reducing postural load through ergonomic modifications and postural training can significantly decrease musculoskeletal symptoms [21].

Ergonomic assessment and workplace modifications

Ergonomic assessment and workplace modification represent crucial components of comprehensive rehabilitation for agricultural injuries. Physiotherapists with specialized training can conduct on-farm evaluations to identify injury risk factors and recommend practical modifications that prevent re-injury and facilitate sustainable return to work [22].

Ergonomic interventions in agricultural settings encompass physical, organizational, and cognitive domains. Physical ergonomic modifications include improvements in equipment design (ergonomically designed hand tools, adjustable tractor seats, mechanized lifting devices), workstation layout (raising work surfaces to reduce stooping, improving material storage accessibility), and use of assistive devices (long-handled tools, wheeled carts, mechanical aids) [7]. Evidence from the agricultural ergonomics literature demonstrates that well-designed ergonomic interventions can significantly reduce musculoskeletal disorder incidence and improve worker comfort [23].

Organizational ergonomic strategies address work scheduling, task rotation, and rest break patterns. Implementing job rotation systems that alternate between different task demands allows workers to use varying muscle groups and reduce cumulative strain from repetitive movements [2]. Structured rest breaks, particularly during peak demand periods such as harvest season, provide essential recovery time that mitigates fatigue-related injury risk. Studies suggest that incorporating regular breaks when working in sustained awkward postures can help reduce chronic musculoskeletal pain [19].

Cognitive ergonomic approaches involve education and training that enhances workers' knowledge of injury risk factors, proper equipment use, recognition of early musculoskeletal symptoms, and strategies for self-management. Educational interventions have demonstrated effectiveness in enhancing workers' knowledge and reducing musculoskeletal disorder risk when delivered through multi-modal formats including workshops, printed materials, and hands-on demonstrations [24].

Pain management strategies

Chronic pain management represents a significant challenge in agricultural injury rehabilitation, as many farmers and farm workers continue working despite persistent pain due to economic necessity, seasonal demands, and cultural factors that normalize pain as an inevitable aspect of farming life. Physiotherapists employ multi-modal pain management strategies that address both nociceptive and neuroplastic pain mechanisms [25].

Education about pain neuroscience helps workers understand that persistent pain does not necessarily indicate ongoing tissue damage, reducing pain-related fear and catastrophization that contribute to disability. Graded exposure approaches systematically increase activity levels despite pain, helping workers overcome kinesiophobia (fear of movement) that often develops following agricultural injuries [25].

Heat and cold modalities offer accessible pain management tools for agricultural workers. Ice application addresses acute inflammatory responses following injury or exacerbation, while heat application before work activities may improve tissue extensibility and reduce pain-related muscle guarding. These modalities are particularly practical for farm workers given their low cost, accessibility, and ease of independent application [13]. Transcutaneous electrical nerve stimulation (TENS) provides another non-pharmacological pain modulation option, though evidence for its effectiveness shows variability across studies [15].

Patient education and self-management

Education and self-management training empower agricultural workers to take active roles in their recovery and injury prevention. Evidence from systematic reviews indicates that education is most effective when combined with other interventions such as exercise and manual therapy rather than as a standalone treatment [15].

Effective education programs for agricultural workers address multiple domains: pathoanatomy and healing timeframes, activity modification strategies, proper tool use and maintenance, importance of regular breaks, early recognition of symptom exacerbation, and long-term self-management strategies [24]. Content delivery should be tailored to agricultural workers' schedules, literacy levels, and learning preferences, utilizing practical demonstrations, visual aids, and hands-on practice.

Self-management training includes teaching workers to monitor symptoms, adjust activity levels appropriately, implement home exercise programs independently, and recognize when professional consultation is warranted. Providing written instructions with illustrations, instructional videos, or digital resources can reinforce education and support adherence to home programs [18]. Research indicates that self-management strategies incorporating ergonomic awareness and safe work practices can result in reduced overall discomfort ratings among agricultural workers.

Discussion:

Integration of evidence into agricultural rehabilitation practice

The synthesis of current evidence reveals several key principles for optimizing physiotherapy interventions in agricultural injury rehabilitation. First, multimodal treatment approaches that combine manual therapy, therapeutic exercise, ergonomic modifications, and education consistently demonstrate superior outcomes compared to single-intervention strategies [12]. This finding aligns with the biopsychosocial nature of agricultural injuries, where physical impairments interact with psychological factors (fear of re-injury, work stress) and social determinants (economic pressures, limited access to healthcare).

Second, interventions must be functionally oriented rather than solely symptom-focused. While pain reduction remains an important goal, rehabilitation programs should primarily emphasize restoration of work capacity, improvement of functional abilities, and facilitation of sustainable return to agricultural activities [14]. The Cochrane review on exercise therapy demonstrated that exercise is more effective than education alone (mean difference -12.2, 95% CI -19.4 to -5.0) for chronic low back pain outcomes, highlighting the importance of active interventions [15].

Third, the specific demands of agricultural work necessitate individualized treatment approaches that consider the unique biomechanical requirements of different farming operations. A dairy farmer facing overhead reaching demands during equipment maintenance requires different rehabilitation strategies compared to a row-crop farmer experiencing lower back pain from prolonged tractor operation [7]. Physiotherapists must conduct thorough occupational analyses to tailor interventions to specific work contexts.

Challenges in implementation

Despite robust evidence supporting physiotherapy interventions, multiple barriers impede optimal rehabilitation service delivery to agricultural populations. Geographic isolation of many farming communities limits access to specialized rehabilitation services, with farmers often traveling considerable distances to reach physical therapy clinics. This access barrier is particularly pronounced in rural areas of low- and middle-income countries where healthcare infrastructure is limited [5].

Economic factors present significant challenges, as many agricultural workers lack comprehensive health insurance, face high out-of-pocket costs for rehabilitation services, and experience income loss during treatment periods. Self-employed farmers may feel unable to take time away from essential farm operations, particularly during critical seasons such as planting or harvest [6]. This economic pressure often results in delayed care-seeking, abbreviated treatment courses, and premature return to work.

Cultural factors within agricultural communities may influence rehabilitation engagement. Research indicates that farmers often normalize musculoskeletal pain as an unavoidable aspect of farming life, potentially leading to delayed treatment and chronic disability [4]. Traditional views of masculinity and self-reliance may discourage help-seeking behaviors, particularly among male farmers. Physiotherapists must recognize and address these cultural factors through sensitive communication and culturally appropriate intervention strategies.

Knowledge gaps among rehabilitation professionals represent another implementation barrier. Many physiotherapists receive limited training in agricultural occupational health, ergonomics specific to farming operations, and the unique psychosocial context of agricultural work [7]. Continuing education programs aim to build physiotherapists' competencies in assessing and treating agricultural workers; however, broader dissemination of specialized training remains necessary to ensure adequate workforce capacity.

The role of technology in agricultural rehabilitation

Emerging technologies offer promising opportunities to enhance physiotherapy service delivery to agricultural populations while addressing traditional access barriers. Telerehabilitation enables remote delivery of assessment, exercise instruction, and progress monitoring through video conferencing platforms. This approach proves particularly valuable for geographically isolated farmers who face transportation barriers to in-person care [18].

Wearable sensors and instrumented devices provide objective data on movement patterns, loading asymmetries, and exposure to ergonomic risk factors during actual farm work. Real-time biofeedback from these devices helps workers modify high-risk movement patterns and improve adherence to postural recommendations. Mobile health applications support home exercise program adherence through exercise reminders, instructional videos, and progress tracking features, accommodating the variable schedules and autonomy-oriented preferences common among agricultural workers.

However, technology implementation must consider the agricultural context, including variable internet connectivity in rural areas, concerns about device durability in harsh farm environments, and varying levels of technology literacy among farmers. User-centered design approaches involving agricultural workers in technology development help ensure practical, acceptable solutions.

Prevention and health promotion

While rehabilitation addresses existing injuries, physiotherapists increasingly recognize opportunities to contribute to primary prevention of agricultural injuries through health promotion initiatives. Ergonomic assessments conducted proactively before injury occurrence identify risk factors enabling preventive modifications [23]. Pre-season conditioning programs prepare agricultural workers for peak physical demands, potentially reducing injury incidence during intensive work periods.

Community-based group exercise programs designed for farmers address multiple health benefits beyond injury prevention, including cardiovascular health, mental wellbeing, and social connection. These programs must accommodate agricultural schedules, with offerings during off-season periods or early morning or evening times that align with farm work patterns. Farm safety workshops that incorporate physiotherapy expertise on proper body mechanics, conditioning strategies, and early symptom recognition reach broader audiences than individual clinical encounters [24].

Future research directions

Despite the growing evidence base, substantial research gaps remain regarding physiotherapy interventions for agricultural injuries. Most existing research originates from high-income countries, with limited evidence from low- and middle-income countries where the majority of agricultural workers reside. Cultural, environmental, and resource differences necessitate validation of intervention approaches across diverse agricultural contexts.

Randomized controlled trials specifically examining agricultural worker populations remain scarce, with much current evidence extrapolated from general occupational rehabilitation research. Trials designed around the unique characteristics of agricultural work, including seasonal demands, self-employment status, and diverse physical requirements—would strengthen the evidence base for practice recommendations.

Long-term outcomes research examining sustained return to work, prevention of recurrent injuries, and career longevity among agricultural workers receiving physiotherapy interventions would inform practice and policy. Current evidence predominantly focuses on short- to medium-term outcomes (up to six months), with limited data on whether intervention benefits persist over years.

Cost-effectiveness analyses comparing different physiotherapy intervention strategies for agricultural injuries could guide resource allocation and policy decisions. Given the economic constraints faced by many farmers and agricultural healthcare systems, understanding which interventions provide optimal value becomes crucial for implementation and sustainability.

Conclusion:

Physiotherapy interventions combining manual therapy, therapeutic exercise, ergonomic modifications, and patient education produce clinically meaningful improvements in pain, function, and work capacity among injured agricultural workers. Implementation requires individualized approaches considering specific biomechanical demands, seasonal work patterns, and psychosocial factors unique to agricultural communities. Despite challenges including geographic isolation, economic constraints, and limited specialized training, emerging technologies like telerehabilitation offer promising solutions. Future research should prioritize randomized controlled trials in agricultural populations, long-term outcome studies, and implementation strategies addressing rural healthcare delivery barriers to reduce the substantial burden of musculoskeletal disorders in this vital workforce.

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SCOPE OF USING PLANT BIOSTIMULANTS IN INPUT INTENSIVE AGRICULTURE

Seema Bhagowati*, Kaberi Mahanta, Samiran Pathak,
Mosfiqual Hussain, Dalim Pathak, Sarat Saikia and Pradip Mahanta
Assam Agricultural University - Horticulture Research Station (AAU-HRS),
Kahikuchi, Guwahati-17, Assam
*Corresponding author E-mail: seema.bhagowati@aau.ac.in

Abstract:

A plant biostimulant is any material or microorganism applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, irrespective of their nutrient content. By extension, plant biostimulants also designate commercial products containing mixtures of such substances and/or microorganisms. Based on their origin, these are categorized into two broad groups: non–microbial biostimulants (chitosan, humic and fulvic acids, protein hydrolysates, phosphites, seaweed extracts, and silicon) and microbial biostimulants (arbuscular mycorrhizal fungi, plant growth–promoting rhizobacteria, and *Trichoderma* spp.). Direct soil application, foliar application, and fertigation are some of the methods of application of biostimulants. They ultimately accelerate the process of crop growth and development and also crop quality. Biostimulants differ from manures and fertilizers according to their usage in minute quantities (du Jardin, 2015). Use of biostimulants could help in maintaining ecological balance by reducing the usage of pesticides and chemical fertilizers or heavy metals for agricultural practices. Considering its immense potential, the European Commission has set a goal to replace 30% of chemical fertilizers with organic–based inputs by the end of 2050 (Hansen, 2018).

Introduction:

One of the main challenges facing input intensive agriculture is finding a sustainable system of feeding the rising world population. Utilization of agrochemicals to enhance food production is becoming unsustainable because of indiscriminate use, prompting stricter regulations. Moreover, there is growing consumer demand for ecological products, particularly since the COVID-19 pandemic. Products with "BIO" or "ECO" labels, indicating sustainable production systems free of agrochemicals, are regarded as healthier alternatives to conventionally produced foods. The need to maintain product quality standards at the highest level is evidenced by the data provided by the Food and Agriculture Organization of the United Nations (FAO), which highlights that 90% of vitamin C and 60% of vitamin A consumed by the human population come from agricultural crops (Bulgari *et al.*, 2019). Therefore, it is important to guarantee both quality standards and food security of the population. So, there is an urgent need to develop more sustainable agricultural systems capable of providing food for growing population while minimizing the environmental impact. Overcoming the increasingly adverse anthropological and edaphoclimatic conditions that limit production performance is imperative. Moreover, the long processes of genetic improvement through breeding developed over the years in crops are reaching the limit of their potential. Given that improving crop tolerance to climate change by genetic modifications or in vitro selection takes years to accomplish, it is of paramount interest to search for alternative strategies with a more immediate impact. The use of biostimulants among sustainable agricultural practices is gaining popularity as a promising, safe, and ecological alternative to improving crop production performance.

Definition:

Prior to the term "biostimulant", the terms "biogenic stimulators" or "biogenic stimulants" were used to refer to substances synthesized in tissues under stressful, but not lethal, conditions, which stimulated the vital reactions of the organism. The term "biostimulant" was used for the first time in a research article by Russo and Berlyn published in 1991. In December 2018, the first statutory language regarding plant biostimulants was provided in the Farm Bill (www.congress.gov). It describes a plant biostimulant is any material or microorganism applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, irrespective of their nutrient content. By extension, plant biostimulants also designate commercial products containing mixtures of such substances and/or microorganisms. The definition provided in the 2018 Farm Bill is consistent with the definition currently proposed by the European Union (http://www. biostimulants.eu/).

Categories:

Based on their origin, these are categorized into two broad groups:

1. Non–microbial biostimulants (chitosan, humic and fulvic acids, protein hydrolysates, phosphites, seaweed extracts, and silicon)

- Chitosan & Other Biopolymers: Chitosan is a plant biostimulant that is derived from the biopolymer chitin, which is a fibrous substance used in the cell walls of fungi. Chitosan has been used to increase plants' ability to handle abiotic stressors like cold and hot weather conditions.
- Humic and Fulvic Acids: Decay of organic matters such as plant, animal, and microbial residues through biochemical reactions of soil microbes leads to formation of these biostimulants naturally in the soil. These organic acids enhance nutrient availability and improve soil structure. By chelating essential nutrients, they facilitate better uptake by plants and stimulate beneficial microbial activity, promoting a healthier soil ecosystem.

This leads to increased crop resilience against diseases and stresses while reducing the need for synthetic fertilizers.

- Protein Hydrolysates: These amino acids play a crucial part in enhancing plant growth and resilience. When incorporated into biostimulant formulations, they help improve nutrient uptake, stimulate root development, and enhance stress tolerance in plants. This is particularly beneficial in agricultural settings, where plants are often subjected to abiotic stresses such as drought or salinity.
- Seaweed Extracts & Botanicals (SWE): SWE can alter the physiochemical nature of soil by altering the nutrient composition, enhancing the growth of beneficial microorganisms, and helping retain more water in the soil. In plants, its role varies from ameliorating nutrient stress to abiotic and biotic stresses by triggering various stress–responsive pathways, as it contains many secondary metabolites that participate in signal transduction.

A. Silicon: In the soil, silicon usually exists as insoluble quartz or silicates that are chemically bound to metals. In the soil solution, silicon occurs as non-ionic silicic acid, which is easily taken up by plant roots and moved throughout the plant. The highest concentration of silica deposition is found around the stomata. These phytoliths increase leaf mechanical strength and erectness, thereby increasing light interception and photosynthesis. They also modulate nutrient and water mobility and increase plant resistance to abiotic stresses, diseases, and pathogens, although the exact mechanisms are not fully understood.

2. Microbial biostimulants (MBBts, arbuscular mycorrhizal fungi, plant growth–promoting rhizobacteria, and *Trichoderma* spp.): These microbial inoculants play a crucial role in nutrient acquisition through solubilization of phosphate, siderophore synthesis, N–fixation, and disease suppression. MBSts are involved in various signaling cascades through the nature of phytohormones, secondary metabolites, amino acids, polysaccharides, and antibiotics (Gupta *et al.*, 2021)

Application methods and mode of action: Direct soil application, foliar application, and fertigation are some of the methods of application of biostimulants. They ultimately accelerate the process of crop growth and development and also crop quality. Biostimulants differ from manures and fertilizers according to their usage in minute quantities (du Jardin, 2015). Use of biostimulants could help in maintaining ecological balance by reducing the usage of pesticides and chemical fertilizers or heavy metals for agricultural practices. Considering its immense potential, the European Commission has set a goal to replace 30% of chemical fertilizers with organic–based inputs by the end of 2050 (Hansen, 2018).

Modes of action/mechanisms of action

Following steps of biostimulants activities are found after their application:

(1) diffusion into plant cells, translocation and transformation in plants,

(2) gene regulation, plant signalling and control of hormonal status,

(3) metabolic activities and consolidated whole plant reaction

Differences between Plant Biostimulants and Traditional Fertilizer (L. Robinson, 2025)

Factors	Plant Biostimulants	Traditional Fertilizer
Functionality	Fertilizers primarily supply essential nutrients like nitrogen, phosphorus, and potassium that plants need for growth. Their primary role is to directly nourish the plant by replenishing nutrient levels in the soil.	Biostimulants, on the other hand, do not directly provide nutrients. Instead, they enhance a plant's ability to absorb and use nutrients more efficiently, stimulating natural processes that promote growth, resilience, and productivity.
Effect on Plant Health	They are nutrient-based and focus on feeding the plant to ensure plant growth.	Biostimulants take a broader approach by focusing on overall plant health, improving stress tolerance, and enhancing the plant's response to environmental conditions like drought or extreme temperatures.
Impact on Soil Health	Fertilizers, especially synthetic ones, can sometimes lead to soil degradation over time if not managed carefully, as excessive use can cause nutrient imbalances and harm soil microorganisms.	Biostimulants contribute positively to soil health by improving the microbial environment and encouraging beneficial biological activity that supports long-term soil fertility.
Regulation	Fertilizers are strictly regulated based on their nutrient content and effects on the environment.	Biostimulants are typically less regulated and fall into a separate category. They are defined by their role in enhancing the plant's internal processes rather than acting as a direct source of nutrients.
Environmental Impact	Fertilizers can lead to runoff and pollution if over-applied, contributing to issues like eutrophication in water bodies.	Biostimulants offer an environmentally friendly solution by reducing the need for excessive fertilizer use and minimizing harmful environmental impacts.

Role of biostimulants in plant growth promotion:

1. Nutrient acquisition and mobilization: Biostimulants are well known for their role in nutrient uptake and mobilization. Carbon–rich humic acids are rich nutrient reservoirs. Fulvic acid enhances the ability of the plant to acquire more nitrogen (NO_3) through increased nodulation, improved protein activities involved in NO_3 uptake and assimilation.

- Implications of biostimulants for abiotic stresses tolerance: Fig 1(A, B) represents role of biostimulants in mitigating the adverse effects of stresses on plants through several mechanisms. Few implications of abiotic stresses are as follows:
- Drought stress tolerance: biostimulants application also induces tolerance to several biotic and abiotic stresses in agricultural and horticultural crops. For example, a foliar application of pollen grain extract (PGE) @ 1 g/L on Ocimum basilicum improved relative water content and water use efficiency, lowered electrolyte leakage, enhanced plant growth, antioxidant enzyme activities, and essential oil productivity under drought conditions (Taha *et al.*, 2020). Biostimulants like seaweed extracts, humic substances, amino acids, protein hydrolysates, and several beneficial microorganisms on vegetables work against the most common abiotic stresses, including drought stress (Bulgari *et al.*, 2019). The mechanisms of salt and drought involve (a) reduced level of hydrogen peroxide and lipid peroxidation, (b) enhanced proline content, (c) differential regulation of gene expression under stress conditions, (d) improving the soil physicochemical and biological attributes, and (e) enhance the root growth of the plants.

A. ***Salinity stress tolerance***: Biostimulants alleviate the salinity stress in different plant species through modification of physiological processes and consequently optimize productivity and growth in the plant. Biostimulants of different origins improve the plant's resistance to salinity conditions by upregulating the genes responsible for stress tolerance.

B. ***High–temperature stress tolerance***: Biostimulants, including microbial-biostimulants, could render an important stimulatory role in mitigating plant responses to heat stress. The synthesis of ROS–degrading enzymes could enhance the heat stress tolerance in plants.

C. ***Low–temperature stress tolerance***: Microbial-biostimulants can help to reduce the effect of chilling temperatures in plants by producing growth–related hormones or that ethylene concentration. Applying soil with psychrotolerant (cold tolerant) bacteria can offer chilling tolerance. The psychrotolerant soil bacterium *Burkholderia phytofirman* is a PGPR capable of colonizing multiple plant species.

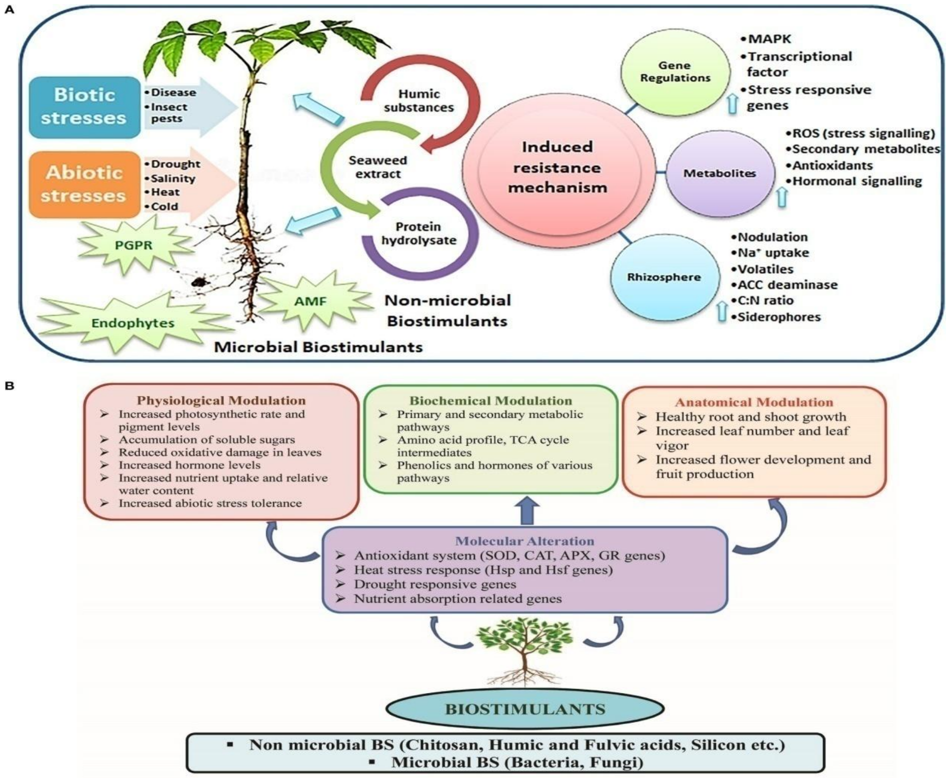

Figure 1 (A, B). Role of biostimulants in mitigating the adverse effects of stresses on plants through several mechanisms (molecular alteration, physiological, biochemical, and anatomical modulations). (Source: Bhupenchandra *et al.,* 2022).

2. Product Quality Improvement

Biostimulants can contain particular growth-promoting bacteria for increased crop yields. When applied to the seed, biostimulants have been known to increase the leaf area, height, and development of seedlings. The application of microbial plant biostimulants is capable of modifying primary and secondary metabolism in plants. Consequently, it helps in the accumulation of anti-oxidant molecules, which is beneficial for humans. biostimulants can optimize grain fill by boosting drought protection during the vital grain fill phase, allowing the plant to take in more water. They can also aid in colouring fruit and postharvest quality.

Conclusion:

Biostimulants have proved their significant potential in alleviating the abiotic stressors intensified by climate change, while maintaining crop output, productivity, and quality to ensure food and nutritional security. These organic agro-inputs seem to be a viable alternative to synthetic protectants and offer a possibility for establishing highly sustainable and environmentally friendly agriculture practices. However, it is essential to comprehend and disseminate understanding regarding the fundamental knowledge of these organic-based products among small and marginal farmers.

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ADVANCES AND GLOBAL PERSPECTIVES IN POULTRY SCIENCE

Pratibha N. Jadhav

Department of Zoology,

M.V.P. Samaj's, Arts, Commerce and Science College, Nandgaon, Nashik, Maharashtra

Corresponding author E-mail: pratibhajadhavzoo@gmail.com

Abstract:

Poultry science is one of the fastest-growing segments of global animal agriculture, encompassing the production, health, nutrition, genetics, and welfare of domesticated birds such as chickens, turkeys, ducks, and quails. Over the past five decades, the poultry farming has undergone profound transformation, driven by technological innovations, improved breeding programs, advanced nutrition, and enhanced biosecurity measures. This chapter provides a comprehensive overview of global poultry production systems, key scientific advancements, sustainability challenges, welfare concerns, and the emerging role of biotechnology and artificial intelligence in modern poultry management.

Keywords: Poultry Science, Global Production, Genetics, Sustainability, Welfare, Biotechnology, Climate Change.

Introduction:

Poultry production is a keystone of global food security and rural development. It contributes significantly to the supply of high-quality protein through meat and eggs while providing livelihoods for millions of smallholder farmers worldwide. According to the Food and Agriculture Organization (FAO, 2023), poultry meat accounts for more than 39% of global meat production, making it the most consumed animal protein globally.

The expansion of poultry production has been driven by scientific innovation and technological integration. Advances in breeding programs, feed formulations, and housing systems have enhanced productivity and animal welfare (Leeson and Summers, 2021). However, global challenges such as disease outbreaks, antimicrobial resistance, and environmental concerns necessitate sustainable and ethical solutions.

Global status and distribution of poultry production

The poultry farming has achieved exponential growth due to rising consumer demand, efficient production systems, and rapid urbanization. According to FAO (2023), poultry meat production reached over 138 million tonnes globally in 2022. Major producers include the United States, China, Brazil, and India.

Regional overview

- Asia: China and India dominate egg and broiler production, with increasing demand for value-added products.

- Europe: Focuses on animal welfare and antibiotic-free production systems.
- North America: Integrates large-scale automation and precision feeding systems.
- Africa: Emerging market with potential for smallholder-based growth.

Economic importance

At the global level, poultry contributes billions of dollars to agricultural GDP. Poultry contributes significantly to GDP and provides income opportunities, especially for women and rural households (Ravindran, 2019). Beyond its economic significance, poultry offers social benefits by enhancing nutritional security, particularly in developing countries where meat and egg consumption is increasing rapidly.

Genetic improvement and breeding strategies

Genetic selection has been essential in enhancing growth rate, feed efficiency, and resistance to disease (Hocking, 2014). Commercial broilers now reach market weight in less than six weeks—a significant improvement compared to 12–14 weeks in the 1960s.

Modern breeding technologies

Advances such as genomic selection, marker-assisted breeding, and CRISPR-Cas9 gene editing enable targeted improvements in productivity and disease resistance (Van Eenennaam, 2021).

Conservation of indigenous breeds

While intensive breeding has boosted production, genetic diversity among local breeds is declining. Conservation of native poultry genetic resources is essential for long-term sustainability and adaptation to local environments.

Poultry nutrition and feed innovations

Nutrition accounts for 60–70% of poultry production costs. Hence, optimizing feed formulations is critical for profitability and sustainability.

Feed ingredients

Corn and soybean meal are the predominant feed ingredients. However, fluctuating global prices have encouraged the use of alternative ingredients such as sorghum, sunflower meal, and insect-based protein sources (Veldkamp and Bosch, 2015).

Feed additives and enzymes

Probiotics, prebiotics, and exogenous enzymes enhance gut health and nutrient utilization, reducing dependence on antibiotics (Kogut, 2019).

Precision nutrition

Precision feeding uses data analytics and sensors to adjust nutrient supply dynamically according to the bird’s requirements, minimizing waste and improving efficiency.

Poultry health management

Disease outbreaks such as Avian Influenza, Newcastle disease, and Marek's disease continue to threaten global poultry populations (Hafez and Attia, 2020).

Biosecurity and vaccination

Stringent biosecurity protocols and vaccination programs are the primary tools for disease prevention.

Antibiotic resistance

The overuse of antibiotics has led to antimicrobial resistance (AMR), prompting the search for natural alternatives such as herbal extracts, essential oils, and probiotics.

Emerging technologies in disease detection

Rapid molecular diagnostics, PCR-based tools, and AI-enabled disease surveillance systems are being integrated into farm management (Wang *et al.,* 2022).

Poultry housing, environment, and welfare

Animal welfare has gained global attention. Countries like the EU have imposed restrictions on cage systems, promoting enriched cages or free-range systems.

Housing systems

i) Conventional Cages: High-density but limited movement.
ii) Enriched Cages: Include perches, nesting boxes, and space for natural behaviors.
iii) Cage-Free Systems: Increasingly preferred in welfare-conscious markets (Mench, 2018).

Environmental management

Ventilation, lighting, and temperature control systems enhance bird comfort and productivity. Climate change adaptation strategies—such as heat-resistant breeds—are vital in tropical regions.

Poultry products: processing and quality

Processing technologies have advanced toward automation, traceability, and quality assurance.

Egg and meat processing

Automation ensures hygienic processing and reduces labor costs. The demand for value-added products (e.g., ready-to-cook or fortified eggs) is rising.

Food safety and quality standards

Global markets emphasize Hazard Analysis and Critical Control Points (HACCP) and ISO 22000 certifications to maintain consumer trust.

Sustainability and environmental impact

The poultry sector contributes relatively less to greenhouse gas emissions compared to ruminant livestock. However, challenges persist regarding waste management and feed resource competition.

Resource Efficiency

Improved feed conversion ratios and nutrient recycling systems contribute to environmental sustainability.

Circular Economy Approaches

Poultry manure is being repurposed for biogas production and organic fertilizer, reducing waste footprints.

Emerging frontiers: Biotechnology, ai, and data science

Modern poultry science integrates biotechnology, artificial intelligence, and IoT (Internet of Things) for precision monitoring and decision-making.

Genetic engineering

Gene editing tools such as CRISPR are used to develop disease-resistant strains (Van Eenennaam, 2021).

AI in poultry management

AI-based systems predict disease outbreaks, optimize feed supply, and monitor bird welfare through image and sound analysis (Wang *et al.,* 2022).

Data-driven farm automation

Smart sensors, drones, and cloud-based software facilitate real-time monitoring of temperature, feed intake, and flock health.

Challenges and future prospects

- Despite significant progress, global poultry production faces challenges related to:
- Emerging diseases and AMR.
- Climate change impacts on productivity.
- Welfare regulations and ethical concerns.
- Supply chain disruptions and feed price volatility.

Future directions emphasize sustainable intensification, digital integration, and global collaboration to ensure food security and environmental balance (OECD-FAO, 2024).

Conclusion:

Poultry science stands at the intersection of biology, technology, and sustainability. The integration of genetics, nutrition, welfare, and smart technologies promises to make poultry production more efficient and humane. A global perspective underscores the need for shared research, responsible innovation, and equitable access to advancements, ensuring that poultry continues to play a vital role in feeding the growing world population.

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RIBOFLAVIN- AN IMPORTANT SOURCE OF MILK AND OTHER FOOD PRODUCTS AND ITS BENEFITS ON HUMAN HEALTH

Binod Kumar Bharti*[1], Sonia Kumari[2] and Manish Kumar[1]

[1]Department of Dairy Chemistry,

[2]Department of Dairy Microbiology,

Sanjay Gandhi Institute of Dairy Technology, Bihar Animal Sciences University, Patna

*Corresponding author E-mail: bkbharti30@gmail.com

Abstract:

Riboflavin also known as vitamin B_2 is naturally present in some foods and added to some food products. Riboflavin is an essential component of two major coenzymes namely flavin mononucleotide (FMN) and flavin adenine dinucleotide (FAD). Riboflavin is found in many foods such as dairy products (milk and yogurt), lean meats, organ meats (liver), eggs, and fortified foods (cereals and bread). Nuts like almonds, leafy green vegetables (spinach and mushrooms), and certain types of seafood are good sources of riboflavin. The use of riboflavin-producing strains is used in the production of dairy products like fermented milk, yogurt, and cheese.

Keywords: Riboflavin, Milk, Fermented Dairy Products, RDA, Seafood, Vision, Anemia

Introduction:

Riboflavin is also known as vitamin B_2. It is one of the parts of B-complex vitamins, which are water soluble vitamin. Riboflavin is naturally present in some foods, added to some food products, and also available as a dietary supplement. Riboflavin is an essential component of two major coenzymes namely flavin mononucleotide (FMN) and flavin adenine dinucleotide (FAD). FMN is also known as riboflavin-5'-phosphate. These coenzymes play an important role in the energy production, cellular function, growth and development, and metabolism of fats, drugs, and steroids (Rivin *et al*., 2010; Said *et al*., 2014). More than 90% of dietary riboflavin is present in the form of FAD or FMN and the remaining 10% of dietary riboflavin is present in free form and glycosides or esters (Said *et al*., 2014; Institute of Medicine, 1998). Most of the riboflavin is absorbed in the proximal small intestine (McCormick, 2012). The body absorbs little riboflavin from single doses about 27 mg and stores only small amounts in liver, heart, and kidneys. More riboflavin is produced after ingestion of vegetable-based than meat-based foods. Riboflavin is yellow colour and naturally fluorescent when exposed to ultraviolet light (Rivin *et al*., 2010). The ultraviolet and visible light are rapidly inactivating riboflavin and its derivatives. For this sensitivity, the lengthy light therapy to treat jaundice in newborns can lead to riboflavin deficiency. The riboflavin is loosed from exposure to light, so milk is not typically stored in glass containers (Gaylord *et al*., 1986). Riboflavin status is not regularly measured in healthy people.

The regular consumption of the fermented dairy product manufactured using the riboflavin-producing strain is able to decrease the relative liver weight and other abnormalities occurred due to vitamin B_2 deficiency. The use of riboflavin-producing strains in the production of dairy products like fermented milks, yogurts, and cheeses is feasible and economically attractive because it would decrease the costs involved during conventional vitamin fortification and satisfy consumer demands for healthier foods.

Recommended intakes

Intake recommendations for riboflavin are provided in the Dietary Reference Intakes (DRIs) which was developed by the Food and Nutrition Board (FNB) at the Institute of Medicine of the National Academies (IMNA) (Institute of Medicine, 1998). Dietary Reference Intakes is the set of reference values used for planning and assessing the nutrient intakes of healthy people. These Dietary Reference Intakes values vary with the age and sex and also include the following:

i. Recommended Dietary Allowance (RDA): RDA is the average daily level of intake sufficient to meet the nutrient requirements of about (97%–98%) healthy individuals. It is used to plan nutritionally adequate diets for individuals.
ii. Adequate Intake (AI): This level is assumed to ensure nutritional adequacy. It is established when evidence is insufficient to develop an RDA.
iii. Estimated Average Requirement (EAR): EAR is the average daily level of intake estimated to meet the requirements of about 50% of healthy individuals. It is usually used to assess the nutrient intakes of groups of people and to plan nutritionally adequate diets for them. It can also be used to assess the nutrient intakes of individual person.
iv. Tolerable Upper Intake Level (TUL): TUL is the maximum daily intake to cause adverse health effects.

Table 1 lists the Recommended Dietary Allowances (RDAs) for riboflavin for infants from birth to 12 months for male and female.

Table 1: Recommended Dietary Allowances (RDAs) for Riboflavin

Age	Male	Female
Birth to 6 months*	0.3 mg	0.3 mg
7–12 months*	0.4 mg	0.4 mg
1–3 years	0.5 mg	0.5 mg
4–8 years	0.6 mg	0.6 mg
9–13 years	0.9 mg	0.9 mg
14–18 years	1.3 mg	1.0 mg
19–50 years	1.3 mg	1.1 mg
51+ years	1.4 mg	1.2 mg

(Institute of Medicine, Food and Nutrition Board 1998)

Sources of riboflavin

Riboflavin plays an important role in human nutrition. There are many sources of riboflavin in food such as dairy products (milk and yogurt), lean meats, organ meats (liver), eggs, and fortified foods (cereals and bread). Many other good sources are including nuts, leafy green vegetables (spinach and mushrooms), and certain types of seafood. Riboflavin mainly found in animal sources and plant sources. Foods are rich sources in riboflavin like eggs, organ meats (kidneys and liver), lean meats, and milk (Said *et al*., 2014; McCormick, 2012). Some vegetables also contain riboflavin like grains and cereals are fortified with riboflavin in the United States and many other countries (McCormick, 2012). The largest dietary contributors of total riboflavin intake in U.S. men and women are milk and milk products, bread, mixed foods whose main ingredient is meat, ready-to-eat cereals, and mixed foods whose main ingredient is grain. About 95% of riboflavin in the form of FAD or FMN from food is bioavailable up to a 27 mg of riboflavin per meal or dose (Institute of Medicine, 1998). Riboflavin is soluble in water, about twice riboflavin content is lost in cooking water when foods are boiled by steaming or microwaving (Agte *et al*., 2002).

Table 2: Important food sources of riboflavin

Food	Milligrams (mg)	Percent (Daily Value)
Breakfast cereals	1.3	100
Yogurt	0.6	46
Milk, 2% fat, 1 cup	0.5	38
Cheese, Swiss, 3 ounces	0.3	23
Mushrooms	0.2	15
Egg	0.2	15
Salmon, pink, canned	0.2	15
Spinach, raw	0.1	8
Apple, with skin	0.1	8
Kidney beans, canned	0.1	8
Macaroni, elbow shaped, whole wheat	0.1	8
Bread, whole wheat	0.1	8

(USDA, 2019)

Animal sources of riboflavin

There are many animal sources of riboflavin like dairy, meat, eggs, sea foods, vegetables etc. Some of the important animal sources of riboflavin are discussed below:

- Dairy: Milk, yogurt, and cheese are excellent sources of riboflavin.
- Meat: Meat is the important sources of riboflavin like lean beef, pork, and chicken. Organ meats, especially liver, are the richest sources of riboflavin.
- Eggs: Eggs are also a good source of riboflavin.
- Seafood: Some seafood fish like salmon, and clams are important sources of riboflavin.

Plant-based and fortified sources of riboflavin

- Fortified foods: Many breakfast cereals, breads, and grain products are enriched with riboflavin.
- Vegetables: Many vegetables are the important sources of riboflavin like mushrooms, spinach, and other leafy greens.
- Nuts: Almonds are a good source of riboflavin.
- Legumes: Beans, peas, and lentils also contain riboflavin.

Deficiency of riboflavin

A deficiency of riboflavin in milk and milk products refers to a situation where a diet lacking in milk. In addition to inadequate intake, causes of riboflavin deficiency can include endocrine abnormalities like thyroid hormone insufficiency and some diseases (Rivin *et al*., 2010). The signs and symptoms of riboflavin deficiency is also known as ariboflavinosis such as skin disorders, hyperemia and edema of the mouth and throat, angular stomatitis, cheilosis (swollen, cracked lips), hair loss, reproductive problems, sore throat, and degeneration of the liver and nervous system (McCormick, 2010). Riboflavin deficiency of people has deficiencies of other nutrients, signs and symptoms might reflect with other deficiencies. Severe riboflavin deficiency can impair the metabolism of other nutrients like B vitamins, through diminished levels of flavin coenzymes. Riboflavin deficiency is severe and prolonged indicates anemia and cataracts (Rivin *et al*., 2010). It is more common in people with low intake of milk products and meat, and can affect people who are vegan or have specific lifestyle factors such as pregnancy, lactation, or advanced age.

Deficiency of riboflavin causes many risk factors in human health. Some of the risk factors are discussed below-

i. **Inadequate dietary intake:** The direct cause is not consuming enough riboflavin from different sources like milk and meat.

ii. **Low consumption of milk:** Lower milk consumption has sign to poor riboflavin status in some people.

iii. Risk groups: Riboflavin deficiency indicates at higher risk in pregnant or lactating women, lower income group people, the elderly, and individuals with high physical activity levels.

iv. Combination with other deficiencies: In this case, riboflavin deficiency is rare. It occurs deficiencies of other B-complex vitamins.

v. Food storage: Storing milk in glass containers can lead to riboflavin degradation due to exposure of light.

Health Benefits of Riboflavin

Riboflavin plays important role in human health. Riboflavin mainly plays important role in migraine headaches and cancer. Major health benefits of riboflavin are discussed below-

Migraine headaches

Migraine headaches typically produce intense pulsing pain in one particular area of the head. These headaches are sometimes preceded by aura like transient focal neurological symptoms before or during the headaches. Mitochondrial dysfunction is to play a causal role in some types of migraine (Yorns *et al*., 2013). Riboflavin is required for mitochondrial function for potential use of riboflavin to prevent migraine headaches (Di Lorenzo *et al*., 2009).

Cancer prevention

Riboflavin helps to prevent the DNA damage caused by many carcinogens by acting as a coenzyme with several different cytochrome P450 enzymes (Rivin *et al*., 2010). A few studies have produced conflicting results on the relationship between riboflavin intakes and lung cancer risk. The average riboflavin intake among was 2.5 mg/day. Riboflavin prevents cancer-causing substances called carcinogens from damaging cells. A Women's Health Initiative studied that participants who got more riboflavin in their diets had a lower risk of colorectal cancer.

Protect vision

A diet rich in riboflavin (vitamin B2) and other B-complex vitamins may lower risk of cataracts. These cloudy areas on eye lenses cause vision problems like blurred or double vision. People with severe, prolonged riboflavin deficiency are most at risk for developing cataracts.

Prevents anemia

Riboflavin helps to body absorb iron. Not getting enough riboflavin puts at risk for iron-deficiency anemia. "People with sufferer of anemia feel extremely tired, look pale and bruise easily. They don't have enough iron to make healthy red blood cells. The Red Blood Cells carry oxygen throughout the body. Pregnant women and children are most at risk for anemia due to riboflavin deficiency.

Conclusion:

Riboflavin is one of the parts of B-complex vitamins, which are water soluble vitamin. Riboflavin is naturally present in some foods, added to some food products, and also available as a dietary supplement. Riboflavin plays important role in human health. There are many sources of riboflavin in food such as dairy products (milk and yogurt), lean meats, organ meats (liver), eggs, and fortified foods (cereals and bread). Many other good sources include nuts, leafy green vegetables (spinach and mushrooms), and certain types of seafood. Riboflavin mainly found in animal sources and plant sources. Riboflavin mainly plays an important role in prevention of migraine headaches and cancer. Riboflavin deficiency is severe and prolonged indicates anemia and cataracts.

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INTEGRATION OF SMART-SENSING AND ARTIFICIAL INTELLIGENCE FOR SUSTAINABLE TEA CULTIVATION: A GLOBAL PERSPECTIVE

Beatris Topno[1] and Supriya Sonowal*[2]
[1]College of Agriculture,
[2]Department of Tea Husbandry and Technology,
Assam Agricultural University, Jorhat, Assam, India
*Corresponding author E-mail: supriya.sonowal@aau.ac.in

Abstract:

Tea (*Camellia sinensis*) is one of the most consumed beverages worldwide and a major livelihood crop across Asia, Africa, and South America. However, the traditional methods of tea cultivation are facing severe challenges due to climate change, fluctuating productivity, soil degradation, and scarcity of labor. The integration of smart-sensing technologies and artificial intelligence (AI) has emerged as a transformative approach to enhance sustainability, efficiency, and profitability in the tea sector. This chapter explores how sensor-based monitoring, data analytics, machine learning, and robotics are revolutionizing tea husbandry from soil management and pest detection to plucking and processing. By comparing global innovations from countries such as India, China, Japan, and Kenya, this chapter presents a holistic overview of how AI-driven agriculture is shaping the next era of smart tea cultivation.

Introduction:

Tea cultivation is not only a cultural symbol but also a crucial component of the global agricultural economy. With more than 6 million hectares under cultivation globally, the tea industry provides livelihoods to millions of smallholders. Tea productivity remains highly vulnerable to environmental stress, labor dependency, and inconsistent agronomic practices. The recent advent of Artificial Intelligence (AI) and smart-sensing technologies in agriculture offers a timely solution. The integration of Internet of Things (IoT) devices, machine learning models, and data-driven decision support systems can provide real-time insights into soil health, pest incidence, and crop performance. The global trend toward smart tea husbandry represents a shift from intuition-based farming to evidence-based precision cultivation.

Smart-sensing technologies in tea cultivation

Smart sensing involves the use of digital sensors that continuously monitor biophysical and environmental parameters to support precision management. In tea plantations, key applications include soil moisture and nutrient sensors, weather and microclimate sensors, and canopy and spectral imaging through drones. In India and Sri Lanka, several tea estates are experimenting with IoT-based field monitoring systems connected to mobile dashboards, enabling real-time decision-making for field managers.

In tea farming, soil sensors such as TDR (Time Domain Reflectometry), FDR (Frequency Domain Reflectometry), and capacitance-based sensors are used to assess soil moisture. By giving information on the water content at various depths in the root zone, these sensors help optimize irrigation schedules. Additionally, since tea soils are frequently acidic, sensors measuring soil temperature and pH are essential for tracking the root environment since they can detect circumstances that could be stressful for tea plants.

Artificial intelligence in tea production systems

AI technologies such as machine learning, computer vision, and deep learning are increasingly used to interpret large datasets generated from sensors and satellite imagery. Major applications include AI-based pest and disease detection, yield prediction models, smart harvesting robots, and AI in processing and quality grading. These innovations significantly reduce dependency on manual labor while enhancing productivity and profitability.

Data-driven soil and nutrient management

Integrating AI with soil sensor data helps develop decision support systems (DSS) for nutrient scheduling. Predictive models can identify nutrient deficiencies and suggest site-specific fertilizer recommendations. Research in China's Zhejiang province demonstrated that AI-based nutrient management improved nitrogen use efficiency by 18% and reduced leaching losses. Similarly, combining soil electrical conductivity data with AI models can generate spatial nutrient maps for more precise input management.

Smart irrigation and water use efficiency

Tea is a moisture-sensitive crop, and climate change has caused unpredictable rainfall patterns across major tea-growing regions. Traditional irrigation techniques frequently depend on set timetables or visual evaluation, which can result in either too much or too little irrigation. An innovative method is provided by AI-supported smart irrigation, which combines automation, data-driven algorithms, and sensors to deliver water exactly where and when it is needed.

Smart irrigation systems using IoT-enabled drip and sprinkler setups adjust watering schedules based on real-time soil moisture and evapotranspiration rates. In Kenya, AI-based models integrated with remote sensing data have optimized irrigation by 25–40%, improving water-use efficiency without compromising yield.

Climate-smart and sustainable approaches

Smart-sensing and AI technologies are central to building climate-resilient tea systems. By analyzing long-term climatic data, AI can predict drought or frost events and recommend adaptive responses. Moreover, carbon footprint monitoring through sensors and AI-based life cycle analysis tools enables producers to align with sustainability certifications such as Rainforest Alliance and Fairtrade.

Global outlook and future prospects

Globally, research institutions and private enterprises are collaborating to integrate digital innovation into tea husbandry. In Japan, smart-plucking robots and AI-based fermentation monitoring are already in commercial use. China leads in the use of AI algorithms for tea quality grading and e-commerce traceability. Kenya and India are developing low-cost sensor kits and mobile-based AI platforms for smallholders. Future research should focus on developing open-source AI tools, affordable sensors, and farmer-friendly interfaces.

Conclusion:

The convergence of smart-sensing systems and artificial intelligence marks a new era in tea cultivation where every leaf, soil particle, and climatic shift can be digitally tracked and managed. The integration of technology with traditional knowledge will be key to ensuring that tea cultivation remains both profitable and environmentally responsible in the decades ahead.

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TOWARDS SUSTAINABLE FARMING: HUMAN HEALTH DIMENSIONS OF AGROCHEMICAL USE AND MISUSE

Ravindra Kumar*[1], Hitendra Kumar[2] and Kamla Dhyani[3]

[1]Department of Biotechnology,

[2]Department of Entomology,

School of Agricultural Sciences, Shri Guru Ram Rai University,

Dehradun-248001, Uttarakhand, India

*Corresponding author E-mail: ravindrakumar@sgrru.ac.in

Abstract:

A large amount of chemical fertilizers and pesticides have been used in agriculture to improve crop growth and to get protection from pests. Fertilizers are essential for plant growth, but when misused, they can degrade soil health, cause nutrient imbalances, and lead to problems such as soil acidification or salinity. They can also make water polluted and contribute to ecosystem damage. Pesticides like organophosphates, carbamates, and synthetic pyrethroids are dangerous too. They can cause short-term problems like headaches or breathing trouble, and long-term issues like brain damage, hormone problems, birth defects, cancer, and lung diseases. Kids, pregnant women, farmers, and people living in rural areas who use groundwater are especially at risk from polluted food and water. Checking for these harmful substances through methods like testing body samples, looking for chemical remains, and checking water quality is important to know how dangerous things are. To fix these issues, we need to use better farming methods like managing nutrients and pests together, using technology to apply fertilizers more accurately, using safer fertilizers that release nutrients slowly, using natural pesticides, and teaching farmers to adopt better practices. We need to find ways to produce enough food without harming human health or the environment, ensuring safe and resilient food systems for the future.

Keywords: Food Security, Agrochemicals, Human Health, Environmental Sustainability, Agricultural Practices, Sustainable Development

1. Introduction:

The Green Revolution in the middle of the 20th century changed how food is produced around the world. This change happened mostly because farmers started using a lot of chemical fertilizers and pesticides. These chemicals helped crops grow better, made sure there was enough food for more people, and reduced the damage caused by pests. However, using these chemicals too much and not thinking about the long-term effects has caused big worries about the environment and people's health. Fertilizers give plants the nutrients they need, but using too much can pollute the soil, water, and air, which then affects people. Pesticides are meant to kill harmful pests, but they can leave harmful remains in food and the environment, leading to both quick and long-term health problems. It is very important to understand how these chemicals affect people's health so that we can create better and safer ways of farming in the future.

Pesticides particularly belonging to organophosphates, carbamates, and synthetic pyrethroids group can get into the human body through food, water, or work-related contact. When someone is exposed to these pesticides quickly, they might feel sick, dizzy, have skin problems, or have trouble breathing. If someone is exposed to these pesticides over a long time, it can lead to issues with the nervous system, hormone problems, fertility problems, and even cancer.

The assessment of these effects involves toxicological studies, epidemiological surveys, and residue analysis in food and water. Regulatory bodies such as WHO and FAO recommend maximum residue limits and safe application practices to minimize risks.

In short, although fertilizers and pesticides are important for producing enough food, using them without care can harm people's health. It's important to use better ways to manage nutrients and pests, try organic options, and closely check for harmful leftovers to protect human health.

2. Chemical fertilizers: Human health impacts

2.1 Nutrient imbalances and contamination: Nutrient imbalance happens when the amount, timing, or mix of nutrients given to plants does not match what the crops need or what the soil can handle. This means that there is too much or too little of certain nutrients, which can lower crop yields and cause environmental harm. When we use a lot of fertilizers, problems often originate from applying too much nitrogen and phosphorus compared to potassium and other nutrients in small amount. Imbalances can occur in the soil, when too much potassium prevents plants from absorbing magnesium, or when excess nitrogen and phosphorus cause water pollution.

2.1.1) N surpluses and the altered N cycle

- **Nitrate leaching:** When excess nitrogen is applied compared to what the crops need, or when it is applied before the plants can take it up, it turns into nitrate (NO_3^-) form. This nitrate can wash down into the groundwater and can make drinking water unsafe. This may also lead to a condition called methemoglobinemia, or "blue baby syndrome," in babies.
- **Gaseous losses:** Ammonia (NH_3) can escape into the air from sources like urea or ammonium, especially when the soil is too alkaline. It happens when it is applied on the surface, or when the weather is warm and dry. Nitrous oxide (N_2O) is another gas that is released through processes like nitrification and denitrification. These gases contribute to air pollution and global warming.

- **Soil acidification:** Using too much ammonical nitrogen over time causes the release of protons during the nitrification process.

If it is not controlled, the soil becomes more acidic, important nutrients like calcium and magnesium are used up, and the risk of aluminum toxicity increases. It is a well-known problem in areas with high fertilizer use.

2.1.2) P surpluses, legacy P, and eutrophication

- When we keep adding mineral phosphorus to soil, it fills up the spaces in the soil where phosphorus usually sticks. This makes more phosphorus wash away through rainwater and soil erosion. This extra phosphorus ends up in lakes, reservoirs, and coastal areas, causing things like algae blooms, low oxygen levels, and harmful toxins from algae.
- Even if you stop adding phosphorus, the phosphorus that's already stored in the soil and stream sediments can still slowly leak into water over many years or even decades, which slows down the recovery of the ecosystem.

2.1.3) Secondary and micronutrient imbalances

Focusing too much on nitrogen and phosphorus can lead to a lack of sulfur, zinc, boron, and magnesium, especially in soils that already have low levels of these nutrients or when crops take them away quickly. There are also common issues where one nutrient affects another, like too much potassium making it harder for plants to take in magnesium, and soil pH can also play a role, such as high pH making it harder for plants to get enough iron or zinc.

2.1.4) Salinity/sodality and ionic toxicity

In arid and semi-arid regions, salt accumulation from fertilizers and irrigation water increases electrical conductivity (EC) and sodium absorption ratios (SAR), which can damage soil structure, reduce infiltration, and hinder nutrient uptake. Chloride-containing fertilizers can aggravate chloride toxicity in sensitive crops under low leaching conditions.

2.1.5) Tracking harmful substances from fertilizers

Cadmium (Cd) and uranium (U) are naturally present in some phosphate rocks. Using fertilizers that contain a lot of cadmium can increase the amount of cadmium in the soil over time. This cadmium can then move into plants, especially leafy vegetables and grains, and eventually into the food chain. Fluoride from phosphate fertilizers can also build up in the soil. At high levels, this can harm the living organisms in the soil.

2.2) Pesticides inflicted imbalances and pollution

2.2.1) How pesticides move in soil and water?

Pesticides can spread to unintended areas through wind, water runoff, evaporation, drainage, or leaks from equipment. How long they last in the environment depends on how they stick to soil, break down in water, get broken down by sunlight, or are digested by microbes.

Some chemicals, like triazines and neonicotinoids, are mobile and long-lasting, so, they can pollute groundwater and surface water at very low levels.

2.2.2) Effects on soil life and nutrient processes

Some Broad-spectrum insecticides, fungicides and even herbicides can alter the balance of microbes in the soil, thus weakening the arbuscular mycorrhizal fungi (AMF). These changes can slow the process of nitrogen being released from the soil, make it harder for phosphorus to move, and reduce soil structure. This can be seen as a "biological nutrient imbalance," which leads to lower nutrient use efficiency (NUE) and makes it necessary to use more fertilizers over time.

2.2.3) Impacts on ecosystems

Insecticides of dust formulations can harm pollinators and other helpful insects. This can also lower the amount of nutrients that are converted into crop yield, reducing the harvest index. Herbicides that kill water weeds can change the types of life in water bodies. In some cases, this can increase algae growth and worsen harmful algal blooms when nutrient levels are already high.

2.2.4) Human exposure

People are exposed to pesticides over time through food, water, and work.Rules and standards set limits on how much pesticide is allowed in food and water. These limits are often broken in places where pesticide use is not controlled or where there is no enough monitoring.

2.3) How contamination spreads from fields

Nitrogen and phosphorus from fields can run off or drain into water, causing water to become too rich in nutrients.This leads to problems like oxygen depletion, harmful algal blooms, and dead zones in water.• Nitrate can move into groundwater, which can make drinking water unsafe.The WHO sets a limit of 50 mg of nitrate per liter, while the US EPA sets a lower limit of 10 mg of nitrate nitrogen per liter. Ammonia can go into the air and combine with other substances to form fine particulate matter (PM_{25}), and it can also contribute to climate change by releasing nitrous oxide (N_2O).

Pesticides can be carried by water into streams, lakes, and sometimes groundwater.This often happens after heavy rains in short bursts.Phosphorus and pesticides that stick to soil particles can be washed away by erosion, especially in areas where the land is not covered with plants.

2.4) Monitoring and indicators

- **Soil tests**: pH, EC, CEC, Olsen/Bray P, exchangeable K/Mg/Ca, DTPA-Zn, hot-water B; total and mineral N pools.
- **Mass balances**: Field/farm nutrient budgets (inputs – outputs) to identify surpluses “nutrient gap”.

- **Water quality**: Drainage/runoff monitoring of NO_3^-, total N, soluble reactive P (SRP), total P; pesticide screening.
- **Biological indicators**: Soil respiration, microbial biomass C/N, earthworm counts, AMF colonization as early-warning signals of pesticide/fertilizer stress.

2.5) Mitigation and best management practices

- Calibrate to crop need and remove legacy surpluses; use partial-factor productivity and agronomic efficiency metrics.
- Nitrogen application should be split near peak crop uptake, while avoiding pre-monsoon or heavy rainfall events
- Apply phosphorus (P) fertilizer in bands and use starter doses. Always incorporate urea into the soil or use urease inhibitors to prevent nitrogen loss through ammonia (NH_3) volatilization.
- The use of controlled-release nitrogen fertilizers, nitrification inhibitors, and low-cadmium phosphorus sources is recommended where relevant."
- Residue retention, reduced tillage, cover crops, and organic amendments or composts are used to increase soil fertility, improve structure, and enhance overall agricultural sustainability.
- Carbon (C) helps improve soil aggregation, enhances biological nutrient cycling, and reduces runoff.
- Contour farming, buffer strips, grassed waterways, constructed wetlands, bioreactors, and saturated buffers are effective practices to intercept nitrogen (N) and phosphorus (P) before they enter water bodies.
- Adequate leaching fractions, good drainage, application of gypsum to manage sodicity, and careful selection of fertilizer anions help maintain soil health and reduce nutrient losses.
- Integrated pest management (IPM) strategies, including the use of economic thresholds, selective or low-risk pesticides, seed-treatment stewardship, drift-reducing nozzles, vegetated filter strips, and biopesticides where effective, minimize environmental and human health risks.
- The use of low-cadmium (Cd) phosphate fertilizers should be prioritized where supplies allow, and soil and crop Cd levels should be monitored in areas with known contamination risks.
- Nutrient-loss targets should be established at the watershed scale, and measures such as nutrient trading or regulatory caps can be adopted where appropriate, alongside routine monitoring of water bodies and public wells.

- Overuse of phosphate fertilizers contributes indirectly to eutrophication of water bodies, leading to algal blooms that may produce toxins, such as microcystins, which are harmful to human liver and nervous system function.

2.6 Heavy metal contamination

Heavy metal contamination take place when toxic metals like lead, cadmium, mercury, arsenic, chromium, and nickel build up in soil, water, air etc. These metals do not break down easily, so they stay in the environment for a long time. They can build up in the bodies of animals and plants, and then move up the food chain, making them harmful to humans and other living beings. These metals come from many sources, such as factory waste, mining, burning fossil fuels, using too much phosphate fertilizer, using sewage sludge, and throwing away waste in an inappropriate manner.

These metals harm the soil, reduce the number of helpful microbes, and slow plant growth. In plants, they can cause damage to cells, yellowing of leaves, and lower the crop yield. In humans, exposure to these metals can lead to brain and nervous system issues, damage to kidneys, cancer, and problems with development in children.

2.7 Air Pollution from fertilizers

The overuse of chemical fertilizers without proper control is a major cause of air pollution. Fertilizers like urea and ammonium nitrate release harmful gases such as ammonia and nitrous oxide into the air. When ammonia escapes into the atmosphere, it can form tiny particles called PM2.5, which make the air dirty and can harm people's lungs. Nitrous oxide is a strong greenhouse gas that helps global warming and also damages the ozone layer. Chemical fertilizers can also give off volatile organic compounds that mix with nitrogen oxides to make ground-level ozone, a type of harmful air pollutant. Using too much fertilizer harms the air, speeds up global warming, causes acid rain, and messes up ecosystems. Using better methods like precision farming, natural fertilizers, and slow-release fertilizers can help reduce these problems.

3. Pesticides: Human health impacts

3.1 Acute toxicity

Acute toxicity means the bad effects that happen quickly after being exposed to a lot of pesticides in a short time, either once or several times. In people, getting poisoned by pesticides is a big health problem, especially in areas where people work with pesticides a lot, like agricultural farms. The symptoms of acute pesticide poisoning depend on the type of chemical. For instance, organophosphates and carbamates stop an enzyme called acetylcholinesterase, which can cause problems in the brain and nerves. This might lead to headaches, feeling dizzy, lots of saliva, muscle weakness, trouble breathing, and in serious cases, seizures or being in a deep sleep. Organochlorines can cause shaking, fits, and over activity in the brain. Paraquat and similar weed killers can damage the lungs badly and lead to failure in several organs.

How bad the poisoning depends on how the person got exposed—like through breathing, swallowing, or skin contact—what kind of pesticide it was, and how much was involved. If not treated quickly with medical help like cleaning the body, giving medicine to counteract the poison, and supporting the body, it can be very dangerous.

3.2 Chronic health effects

Being around pesticides for a long time, even in small amounts, can be harmful to our health. This is different from sudden poisoning, which happens quickly. Long-term effects build up over time because we keep getting exposed little by little. People can come into contact with pesticides through food that has pesticide leftovers, water that is polluted, working with pesticides, or because pesticides stay in the environment for a long time.

3.2.1. Major chronic health impacts of pesticides include:

- Some pesticides, like organochlorines, glyphosate, and atrazine, have been connected to different types of cancer.
- Organophosphates and carbamates are linked to brain diseases such as Parkinson's and Alzheimer's, as well as problems with thinking and development in children.
- Many pesticides act as endocrine disruptors, which mess with the body's hormones and can cause issues with reproduction, difficulty in having children, and problems with growth and development.
- Breathing in pesticide particles over a long time can lead to asthma, chronic bronchitis, and difficulty in breathing properly.
- Being exposed to pesticides for a long time can make the body's defense system weaker, making it easier to get sick or develop autoimmune diseases.3.2.2. Residues in Food and Water
- Pesticide residues frequently exceed permissible levels in fruits, vegetables, grains, and dairy products. Chronic ingestion through contaminated food chains is a key pathway of exposure for the general population.

4. Vulnerable groups

- Children: Because they have less body weight and are still growing, they are more likely to be affected by nitrate poisoning, brain damage, and problems with development.
- Pregnant Women: Being exposed to pesticides or polluted water during pregnancy can lead to miscarriage, early birth, and issues with the baby's development.
- Farmers and Agricultural Workers: Working with chemicals often without proper protection can cause sudden poisoning or long-term health problems.
- Rural Communities: People who rely on groundwater for drinking are more likely to be exposed to harmful chemicals from fertilizers.

5. Assessment and monitoring approaches

- Biomonitoring: Checking for pesticide breakdown products and nitrate/nitrite levels in the blood and urine of people who have been exposed to these chemicals.
- Food Residue Analysis: Keeping an eye on food items for harmful chemical leftovers to make sure they stay within safe limits set by regulations.
- Water Quality Testing: Watching groundwater and surface water for nitrates, phosphates, and traces of pesticides.
- Health Risk Assessment Models: Calculating the chances of cancer and other health problems from being exposed to farm chemicals over a long time.

6. Mitigation strategies

- Integrated Nutrient Management (INM): Using organic manure, biofertilizers, and carefully applied chemical fertilizers to lower contamination.
- Integrated Pest Management (IPM): Using natural predators, disease-resistant crops, and need based safer pesticides to control pests.
- Regulations and Policies: Making sure pesticides are properly approved, checking for harmful residues, and controlling the quality of fertilizers.
- Protective Measures for Farmers: Wearing safety gear, getting training on how to handle chemicals safely, and running education programs for the community.
- Consumer Awareness: Teaching people to wash, peel, and cook food to cut down on pesticide leftovers.

Conclusion:

Using chemical fertilizers and pesticides has definitely helped increase food production, but it is important to notice the harm they can cause to people's health. These chemicals can lead to sudden poisoning, long-term illnesses, and damage to the environment. Because of this, there is a big need to change how we grow food. We should use safer methods, better manage resources, and have strict rules to protect both people and the planet. To keep food supplies safe and healthy, future farming should focus on natural products, organic methods, and advanced technologies that help use resources more carefully and effectively.

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About Editors

Prof. (Dr.) Sanjay Khajuria, Chief Scientist and Head of Krishi Vigyan Kendra (KVK), Samba, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu, is a devoted agricultural scientist dedicated to advancing rural prosperity through research and innovation. Under his leadership, KVK Samba has made remarkable strides in the Viksit Krishi Sankalp Abhiyan, emphasizing sustainable farming and technological adoption. His research focuses on crop productivity, soil health, and climate-resilient agriculture. Through extensive farmer training, field demonstrations, and outreach initiatives, Dr. Khajuria has strengthened the link between science and society. His unwavering efforts have fostered agricultural growth and socio-economic empowerment of farmers in Jammu & Kashmir, earning him recognition as a visionary leader in agricultural science and rural development.

Dr. Baig Mumtaz, M.Sc., Ph.D., F.S.A.N., serves as Associate Professor and Head of the Department of Botany at Dr. Rafiq Zakaria College for Women, Aurangabad, Maharashtra. A recognized research supervisor at Dr. Babasaheb Ambedkar Marathwada University, she currently guides three Ph.D. scholars. With 25 years of teaching experience, she has significantly contributed to Plant Pathology and Seed Technology research. Dr. Baig has authored 20 textbooks for the B.Sc. syllabus and published over 60 research papers in reputed national and international journals. She has participated in more than 50 academic events, including seminars and conferences. Actively involved in extracurricular activities like herbarium and album preparation, she has received several honors, including the Young Researcher Award (2020), Academic Excellence Award (2022), and International Excellence in Teaching Award (2025).

Ms. Vaishnavi Ghadage serves as Assistant Professor in the Department of Zoology at M.M. College of Arts, N.M. Institute of Science & H.R.J. College of Commerce, Bhavan's College (Autonomous), Andheri West, Mumbai. She holds a Master's degree in Animal Physiology from Bhavan's College and possesses three years of research experience. With two years of teaching experience, she is deeply committed to imparting both theoretical and practical knowledge to students. Her research interests focus on solid waste management and agriculture. Ms. Ghadage has presented her work at several national and international conferences and has published five research papers in reputed Scopus and Web of Science indexed journals. She continues to pursue her passion for teaching and sustainable research contributing to environmental and agricultural advancements.

Dr. Brijesh Kumar, M.Sc., Ph.D. (Soil Science), and NET (ASRB), currently serves as Assistant Professor-cum-Scientist in the Department of Soil Science at Dr. Rajendra Prasad Central Agricultural University, Pusa (Samastipur), Bihar. With over 12 years of teaching, research, and extension experience, he has significantly contributed to soil fertility management and organic farming. Dr. Kumar has published 12 research papers, 7 book chapters, 3 books, 73 popular articles, 3 case studies, and 6 extension folders, and holds 1 patent. He has received several accolades, including the Distinguished Scientist Award, Utkrist Lekhak Award (2018), and Environmentalist Award (2023). Actively participating in national and international conferences, he continues to inspire learners through his expertise in "Soil Facts and Concepts," advancing sustainable soil and environmental sciences.

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