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Balancing Chemical Pesticides and Organic Fertilizers in Garlic Production: A Review of Correlations, Trade-offs, Sustainability, and the Need for ML-Based Decision Support

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Abstract

The Garlic (Allium sativum L.) is a highly valuable horticultural crop with high value, nutritional, medicinal and commercial value which is increasingly depending on synthetic pesticides and conventional nutritional feeds to its increasing production systems. There is some evidence available indicating that the risk of residues, pest resistance, soil degradation, and ecological stress associated with high rates of chemical pesticide use might be decreased through the alternative employment of organic manure and integrated nutrient administration, which are not fully utilized or applied equally even where they have the potential to grow soil organic carbon and nutrient-use efficiency, crop-resilience and bulb-quality. The literature review will be summarized regarding the agronomy of garlic, pest and disease infestations, crop-health monitoring, yield response, and sustainability measurement as the literature attempts to comprehend the relationship that exists between chemical pesticides and the organic fertilizers in a production system. It dwells on correlations between intensity of inputs and pest attack and the health and yield and quality of the plants; agronomic, economic and ecological trade-offs between the different input regimes; the suitability of sustainability indicators of soil organic carbon and bioefficiency ratio and residue burden and input-use efficiency. As observed in the review, another major gap in the current literature is that there were no coherent and garlic-specific machine learning-based decision-support systems capable of processing input data at the field level, soil condition, pest stress, and agro-climatic factors, and transforming them into recommendations applicable to a specific site. This review offers a model of sustainable garlic intensification, and sensible advice to the researcher, extension systems, and agricultural policy by integrating piecemeal evidence and determining the significance of forecasting, information-based advisory instruments.

Introduction

1. Background and Context

Allium sativum L. Garlic a horticultural crop is strategically important in food system, nutritional education of the people as well as agricultural economies. It is also known to have a high value not only as a food commodity but also because of its medicinal and functional properties especially in its bioactive sulfur-based compounds which have seen a long-standing scientific and commercial interest. Garlic is a significant source of farm income in several parts of the world as well as in large belts of garlic production in India since the market value of the crop is relatively high, the crop is storable and is otherwise demanded in both local and export markets. Consequently, the growing of garlic has been a significant source of livelihood among small and medium scale farmers who are interested in finding lucrative sources of crop diversification and increased production systems.

Over the last few years, however, the quest to achieve greater yields and better quality of the bulbs has seen farmers rely on external agricultural inputs. The culture of garlic production has increasingly become more often marked by an increased application of synthetic pesticides and traditional fertilizers to regulate the occurrence of pests, pressure of diseases and nutrient requirements. Even though such inputs can contribute to short-term productivity, their overutilization or imbalanced use has caused great concerns about the long-term sustainability, environmental safety and soil health. Simultaneously, there has been increasing focus on organic fertilizers and integrated nutrient management as either an alternative or a complement to the maintenance of crop productivity and a stable ecological balance.

2. Problem Statement

Reliance on chemical pesticides, underuse or failure to use organic fertilizers or imbalanced application is a significant issue in modern garlic production. Chemical crop protection is practiced in most production settings, where they are implemented on a generalized basis, instead of being applied based on evidence-based, site-specific management. Although they can decrease pest destruction in the short run, these practices increase pesticide remains, pesticide resistance, harm beneficial soil life, and escalate costs of production. On the other hand, organic fertilizers and bio-based nutrient inputs, though shown to be beneficial in terms of soil organic matter, nutrient cycling and crop resilience

are typically applied intermittently or as a secondary consideration to synthetic inputs.

This poses a viable and policy-based quandary; how do producers of garlic guarantee high production, promotable quality and in the meantime, safeguard the quality of the environment, enhance soil fertility and guarantee stability in production in the long term? The question, however, is not whether it is the good choice to work either with chemical or organic methods but the necessity to find an ideal balance between productivity as the input use and sustainability as the farm management.

3. Review Rationale

The literature work presently on the production of garlic has been scattered in various fields such as agronomy, pest and disease control, soil fertility, crop physiology and predictive analytics. Other studies are on the impact of pesticides on pest control and yield, and others are on the impact of organic amendments in enhancing the characteristics of soils and plants. A more limited but growing literature studies the use of statistical and machine learning methods in yield prediction and agricultural decision support. Nevertheless, it is a rare case that these strings of research are assembled in a single framework. There is, therefore, an evident gap in the unified review to critically investigate the interaction of chemical pesticides and organic fertilizers in a garlic system and the implication of such interactions to the health, productivity, sustainability, and design of digital advisors.

4. Aim of the Review

The purpose of the review is to provide a critical synthesis of the existing evidence on the associations between the use of chemical pesticides, application of organic fertilizers, the health indicators of crops, yielding and the sustainability outcome of the production of garlic. It also aims at establishing conceptual, empirical, and methodological gaps in the literature and determining the necessity of machine learning-based decision-support systems that would be able to generate site-specific, data-driven recommendations to support the work of garlic farmers.

5. Review Questions

The review is guided by the following questions:

1. What correlations have been reported between chemical pesticide use and garlic productivity?
2. What effects do organic fertilizers have on yield, pest pressure, and soil health in garlic systems?
3. What trade-offs emerge when balancing productivity, bulb quality, environmental protection, and long-term sustainability?
4. Which sustainability metrics are most relevant for evaluating garlic input-management systems?

5. Why are machine learning-based decision-support systems necessary for this domain?

Literature review Methodology

1. Review Design

The paper will take a systematic-style narrative literature review research design which will help to synthesize evidence on the correlation between chemical pesticides, organic fertilizer, crop health, yield performance, sustainability measures, and digital decision-support in garlic production systems. A narrative review would have flexibility regarding interpretation, whereas a systematic style would enhance the transparency of the article's selection, screening, and theme organization. This is particularly required since the current knowledge base is scattered in the agronomy, plant pathology, soil science, sustainability assessment, and machine learning. The uploaded proposal also recognizes the discontinuity in the existing research and the necessity of a comprehensive, empirical synthesis, which could connect the regimes of inputs with the indices of plant-health, performance in yield, and sustainability.

2. Search Strategy

The literature search would be carried out in the major multidisciplinary and agriculture-focused databases (such as Scopus, Web of Science, Google Scholar, PubMed, CAB Abstracts, and AGRICOLA) so that it was possible to identify research that was peer-reviewed, related to agronomics, environment, and computational research on garlic growing. Crop-specific, input-specific, sustainability-related, and analytics-oriented keywords should be used together in search strategy to achieve the greatest breadth of retrieval and topical accuracy at the same time. The representative search strings will be: a usage of garlic pesticide yield, organic fertilizer soil health on garlic, Allium sativum machine learning decision support, and integrated nutrient management on garlic sustainability. These words would be suitable since the literature base of the proposal includes efficacy of pesticides, organic amendments, crop-health characteristics, integrated nutrient management, and new predictive modeling strategies in garlic as well as Allium systems.

3. Inclusion Criteria

The review must contain the studies that specifically consider garlic (Allium sativum L.), as well as the attentively chosen one that studies extremely close Allium crops in which there are concepts or methodological transfer justifications. The eligible studies must involve one of more of the following areas: chemical pesticides, organic fertilizers, integrated nutrient management, pest and disease incidence, crop-health indicators, yield response, soil health, sustainability metrics, decision-support systems, or machine learning in crop management. To achieve the rigor of the study, the review needs to focus on peer-reviewed journal articles, conference papers, and institutional reports. This criterion is in line with the fact that the proposal relies on agronomic experiments, correlation studies, nutrient- management trials as well as decision-support research based on both agricultural and computational literature.

4. Exclusion Criteria

Included in studies should be those that are enhancing irrelevant crops, studies that are not empirically based and those that lack adequate description of the methodology that can be used to make an analytical comparison. Records in more than one database can be deleted, and poor-quality or non-scholarly material can be filtered out to preserve the integrity of the synthesis. Furthermore, the studies which cover the general sustainability or digital agriculture but have no serious relation to the input management of garlic should not be stored. The significance of these exclusion principles lies in that the proposal clearly points out the lack of coherent datasets and strong comparative evidence, which only methodologically valid and contextually pertinent studies can help with valid synthesis.

5. Thematic Review Framework

The filtered literature must then be sorted into a thematic system under 4 analytical cluster groups namely agronomic effects, pest and disease management, soil and environmental sustainability, and analytical and digital decision-support systems. The former theme documents the evidence of bulb yield, quality characteristics, and the indicator of plant-health. The second covers the activity of pesticides, pest management, and disease management of various management regimes. The third is centered on the soil organic carbon, nutrient-use efficiency, ecological burden, and sustainability in the long term. The fourth is the synthesis of a statistical model, machine learning, and development of decision-support systems to provide site-specific recommendations. This thematic organization is closely connected to the gaps that the proposal identified,

i.e. the deficit of integrated correlation, the absence of sustainability-focused comparative and the necessity of predictive and machine learning-based decision support tools in the domain of garlic cultivation.

Garlic Production Systems: Agronomic And Input Situation

1. General background on the Garlic cultivation

Garlic Allium sativum L. is a high-value bulb crop of major nutritional, medicinal, and commercial value. It is commonly grown as a source of food consumption, storage ability and bioactive sulfur compounds, which affect the demand of consumers and the value market. Agronomically speaking, garlic is an input-sensitive crop in the sense that the process of developing the bulb, the cloves, pungency, and marketable quality strongly depend on the availability of nutrients, moisture regime, pest pressure, and the management of the crop. The uploaded proposal reports that garlic cultivation in Maharashtra is simply more than 100,000 ha and it has been economically significant to the state and country, thus it is the economically significant crop among the small and medium farmers. Concurrently, it exhibits a significant difference in its production performance with respect to agro-ecological regions like Nashik, Ahmednagar, Pune, Jalgaon, and Satara where management results are influenced by the differences in the type of soil, rainfall, and irrigation.

2. Major limitations in the production of garlic

Garlic cultivation is limited by numerous biological and agronomic factors, although this crop has great economic value. Some of the most evident ones are thrips infestation, specifically that of Thrips tabaci, and key fungal infections like purple blotch that directly suppress the well-being of leaves, photosynthetic effectiveness, and yield of the bulb. Other aspects of production, such as the deterioration of the quality of the bulbs, the lack of balance in the nutrients, and the gradual degradation of the soil due to the intensive cultivation with input, is also mentioned in the proposal. These limitations have a connection with each other: pest and disease pressure can contribute to the increased use of pesticides, whereas the lack of nutrients can reduce the vigor of crops and make them more vulnerable to stress. In the same manner, soil erosion compromises the efficiency of nutrient utilization and productivity in the long term. The current literature, used in the proposal, states that plant-health features, including chlorophyll status, bulb diameter, the number of cloves, and the content of pyruvic acid can be also considered as associated with the productivity of garlic which implies that the constraints of production should be regarded as well, in relation to the intermediate indicators of crop-health.

3. Role of External Inputs

In the production systems of garlic, external inputs are hence a point of centrality. The chemical pesticides are usually applied to choke insects and fungi pests and also to shield the saleable crop in challenging market situations. They however, come with residue issues, pest resistance and ecological side effects in case of indiscriminate use. Conversely, organic fertilizers and combined nutrient management strategies play a role in releasing nutrients, conditioning the soil, increasing the organic carbon situation, and supporting microorganisms, thus increasing the long-term yield of the soil and crop resiliency. In this proposal, the authors specifically point out neem cake, water-soluble fertigation, and vermicompost as key ingredients of integrated nutrient strategies in the production of garlic. Notably, neither the chemical nor the organic inputs are fully effective; they interact with irrigation mode, soil texture, climatic variation and varietal response. Therefore, it follows that garlic production should be perceived as a context-specific mechanism where agronomic performance arises because of a process of interaction between the genotype of crops, the environment, and the input management but not because of any practice applied in isolation.

The Use of Chemical Pesticides in Producing Garlic

1. Types and Uses

One of the main elements of modern garlic production systems are chemical pesticides especially when problems with pests and diseases are high. The proposal uploaded reveals various crop-protection chemicals applicable in the management of the garlic crop but including deltamethrin
2.8 EC, fipronil 5 SC, profenofos 50 EC and spinosad 45 SC which will be proposed to be applied at field level based on the concentration, volume of the spray and timing of the application after planting. These are the key groups of insecticidal control that are regularly used against pests affecting the field, and the wider literature surveyed in the proposal also indicates the use of fungicidal handling of the disease purple blotch caused by Alternaria porri. Practically, these chemicals are used to minimize the pest attack, curtail the disease development, and shelter photosynthetically active foliage during the bulb development.

2. Agronomic Benefits

Agronomically, chemical pesticides can create an immediate and highly measurable advantage in the production of garlic in the form of pest incidence suppression and severity of disease reduction. Their major benefit is that they are used to prevent foliage damage, to sustain plant activity and to defend bulb development at risky developmental stages. This proposal reiterates on the importance of farmers increasing the use of synthetic pesticide since they believe that it is associated with better harvest protection and more predictable marketable yield during uncertain field conditions. Timely pesticide application can hence be used as a short-term mitigatory measure in production environments that have thrips pressure, fungal infection, and climatic variability. The body of the literature summarized in the proposal also indicates that the downstream impacts of pest reduction on bulb quality, chlorophyll retention and yield protection exist, even though the magnitude of response is variable across agro-ecology, timing and input combination.

3. Limitations and Risks

Despite these agronomic benefits, the reviewed literature on the proposal shows that there are huge concerns regarding overdependence or imbalance on the use of pesticides. The indiscriminate application of agrochemicals has been associated with residue build up, soil erosion, pest resistance and ecological stress, so pesticide-intensive production of garlic has become more problematic in the sustainability and compliance angle. According to the proposal, excessive application of synthetic pesticides will harm soil microbiota which are useful, increase the production expenses and the chances of exceeding the residue limit in export markets. It also records that in Nashik 25 percent of the garlic samples had surpassed maximum residue levels on deltamethrin and profenofos and that further heavy spraying was a contributor to thrips resistance and decreasing pesticide efficacy across several seasons. These results show that the agronomic benefits of chemical pesticides are counterbalanced by severe long-term risks in concerns with environmental health, regulatory compliance, and economic inefficiency.

4. Garlic and Allium Studies Evidence

The evidence that has been incorporated in the proposal can be said to indicate that the result of pesticides in the garlic and other Allium systems is mixed and tend to be fragmented. Other studies indirectly prove the worth of crop protection by decreased pest pressure, and some studies show that currently, the research does not normally measure pesticide regimes with the required level of precision to determine a strong dose-response relationship. Indicatively, the proposal explains that other recent studies of yield-prediction in Allium crops had pesticide presence only as a binary condition and not measured as a management variable. It also notes that there is no integrated research which combines the dose of pesticides, pest and plant-health indices with yield that covers regions. As a result, although chemical pesticides have undoubtedly been shown to play an important role in the suppression of pests and temporary protection of yields, the existing literature lacks a sufficiently combined system that would allow to establish the optimal level of pesticide application in the garlic systems. The existence of this gap is a good argument in favor of more systematic, data-driven and sustainability-focused analysis of pesticides in the production of garlic.

Integrated Nutrient Management and Organic Fertilizers in Garlic

1. Types of Organic Inputs

Organic manure and integrated nutrient management (INM) techniques are being perceived as vital elements of sustainable production of garlic. The proposal uploaded recognizes some of the significant organic and biologically derived inputs applicable to garlic systems such as vermicompost, neem cake, Azospirillum, phosphate-solubilizing bacteria, compost-based nutrient packages and water-soluble fertigation employed in integrated nutrient schedules. These inputs vary in terms of the dynamics of release of nutrients and functionality. Vermicompost and farmyard manure are mostly useful in increasing soil organic matter and nutrient buffering, neem cake in addition to nutrient value also has bioactive pest-suppressive properties, and biofertilizers have the advantage of enhancing nutrient mobilization and rhizosphere activity. These combined packages are of special importance in garlic since the growth of bulbs and quality of crops is not only affected by the amount of nutrient, but also by the physical status of the soil, the balance of the microbes and the availability of nutrients in the soil at the different stage of growth.

2. Crop Performance

The agronomics of organic fertilizers in garlic is that it contributes to the short-term and long-term soil productivity by contributing to the performance of crops. In the proposal, the organic nutrient use in an integrated way is linked to increase in soil organic carbon, nutrient-use efficiency, plant activity, and bulb yield. Organic amendments also increase the soil structure, increase moisture retention, promotes the beneficial microbial activity, and contributes to gradual release of nutrient which is pertinent in input-sensitive crops like garlic.

The literature review in the proposal also shows that vermicompost and neem cake treatment with biofertilizers can decrease the severity of the disease and enhance yield and quality of the bulb. An example is organic amendments have been reported to minimize the intensity of purple blotch and yield higher compared to chemical-fertilizer-only treatments. This kind of evidence indicates that organic nutrient strategies do not just replace nutrients; they can make crops more resilient and enhance the functional health of the system of production.

3. Constraints and Adoption Problems

Although having the following advantages, there are several practical limitations that limit the use of organic fertilizers in garlic. The release of the nutrients in organic inputs is usually variable, and the effects of organic inputs can be less immediate and predictable as compared to the synthetic fertilizers. Local supply chains may also restrict their availability and transportation, handling, and application demands make labour more intense. The proposal highlights that the adoption of organic fertilizers is still below optimal levels among the smallholders even in cases where they have been reported to be beneficial due to disjointed extension advice, and poor decision-support tools. The adoption may also be discouraged because of costs in cases where short-term payoffs are not clear, in places where farmers already have their own routines which involve chemical inputs. Consequently, most growers use organic inputs on a group basis or supplementally instead of using them as a component of scientifically balanced management system.

4. Garlic Study Evidence

The literature reviewed in the proposal has shown Limited literature on garlic established that integrated treatments are often superior to solely chemical or solely organic strategies in terms of yield, disease control and soil-health. The comparative experiments between organic amendments and conventional ones on the use of fertilizers have indicated that integrated regimes have improved disease management, yield enhancement and long-term soil condition. Nevertheless, the same literature also states that most of the studies are localized, short-term, and with limited links to the wider predictive or optimization models. In its turn, the empirical data confirms the usefulness of INM in garlic, which also highlights the importance of more organized and information-driven analysis of the ways of how the balance between organic and inorganic inputs can be optimized under various production conditions.

Correlations Among Inputs, Crop Health and Yield

The evidence of the production of garlic is growing to indicate that the correlation between farm inputs and the crop output was not linear, independent, and consistent across the production settings. Instead, it is shaped by the interdependent correlation between pesticide dose, the use of organic fertilizers, health of the plants, the performance of yield, and the quality of the bulb. The proposal uploaded clearly states that there are four key dimensions of correlation that need to be synthesised in a systematic manner: pesticide dose and pest incidence, organic fertiliser rate and soil health, plant-health indicators and yield, and combinations of inputs and the quality of the bulb. It also claims that lack of incorporated correlation matrices among these variables is a significant impediment to evidence based garlic management.

Plant-health indicators in the context of garlic literature are necessary variables of intermediate level that relate management practices to the result of agronomic output. The proposal singles out SPAD chlorophyll measurements, leaf-damage measurements, severity of disease, the diameter of the bulb, the number of cloves and the contents of the pyruvic acid as particularly interesting parameters to use in the correlation-based analysis. The values of SPAD are the proxies of the plant nutritional status, whereas leaf-damage scores and the severity of diseases reflect the immediate biological impacts of pest and pathogen pressure. The diameter of the bulb and the number of the cloves are yield-related characteristics and pyruvic acid is a quality indicator correlated with pungency and market price. The available literature reviewed in the proposal indicates that yield variability could be attributed to bulb diameter and the number of cloves together in one of the ancient studies on garlic, and more recent studies documented significant relationships between bulb weight and chlorophyll in leaves. These results prove that yield is not only a result at the end of harvest but a result of many physiological and agronomic interactions.

Using the same evidence, it is possible to say that the use of a balanced input can affect the yield and quality. It was reported that organic amendments, e.g. vermicompost, neem cake, biofertilizers, led to reduced severity of the disease and higher yield compared to chemical-only nutrient management, and changes in nutrient schedules led to better quality of the bulbs. The proposal further adds that the increase of the pyruvic acid content can be accompanied by improvements of the input regimes balance, which is an indication that quality characteristics can respond positively when productivity and plant health are controlled jointly and not separately. Simultaneously, the application of pesticides is also relevant if the retention of foliage is supported and the yield potential is insured using pesticides. Therefore, the critical analytical question is not whether one category of inputs is more important than the other, but the degree of variation through the combinations of different inputs in terms of their agronomic and quality results in different field conditions.

Irrespective of these understanding, correlation studies in garlic are weak in methodologies. The proposal also reveals some of the recurrent constraints which include unification of datasets, small sample sizes, inadequate multivariate modelling, and poor incorporation of environmental covariates like rainfall, temperature, soil texture, and irrigation regime. A large body of literature has documented the effects of isolated treatment without relating them to larger input/output systems, and some predictive studies do not include the variables of organic fertilizer or use the use of pesticides as a binary variable. Consequently, farmers are yet to have a solid empirical information regarding how the intensity of pesticides and organic amendments, crop-health variables, and environmental factors interactively determine sustainable garlic performance.

TRADE-Offs Between Chemical Pesticides and Organic Fertilizers

One of the main themes of the literature of garlic is that input management needs to be assessed using trade-offs and not on an individual basis of yield response. The posted proposal always presents the issue of garlic production as a trade-off situation whereby chemical pesticides could offer a temporary measure of pest control and protection of yields, and the use of organic fertilizers will provide and enhance the long-term sustainability of soil health, nutrient-saving and crop resistance. Therefore, the research question and policy of interest is not whether one input category ought to be substituted by the other but how the two can be brought to balance agronomically and sustainably at the same time. Chemical pesticides may be beneficial in terms of productivity to maximize short-term yields by minimizing the occurrence of pests and severity of diseases at crucial vegetative development and bulb development periods. Their direct response endears them in hazardous environments where crops can easily be damaged to reflect on economic cost. The proposal, however, highlights that excessive use of synthetic pesticides may negate the sustainability in the long run due to issues of accumulation of pesticides, resistance, and ecological stress, and ultimately compromising the production system that will ensure that yields will remain stable in the future. In comparison, organic fertilizers and combined nutrient control can produce slower yet longer-term effects through enhancing soil organic carbon, water-absorbing capacity, nutrient accessibility, and vegetative vitality. This brings a conventional trade-off between the protection of the short-run output and the sustainability of production in the long-run.

The trade-off involved in the economy is also complicated. The heavy chemical reliance can be seen economically detached since pesticides can be economically fast and effective with field pressure, but with consistent application, the inputs costs increase, and the profitability can decrease in the long run, particularly when resistance causes a decrease in its effectiveness. The proposal observes that the integrated organic practices have the potential to yield profitability by enhancing nutrient-use efficiency, soils, and unnecessary chemical application even though initial adoption might entail additional labour, coordination, or uncertainty. Therefore, it is possible that chemical-intensive policies would support short-term domination, and the combined technologies would reduce the cost of production in the long run and enhance the net returns.

The trade-off is intensified even on the ecological perspective. Chemical pesticides can provide effective suppression of pests, but misuse can upset the soil microbiota, ecological overload, and raise the issue of residues. Organic fertilizers, in their turn, are more likely to favour the conditioning of soils, microbial activity, and environmental sustainability, but not necessarily offer the same fast results in pest-control. The management trade-off hence is between relative ease and speed of chemical control and more complex integrated management that involves timing, knowledge and adapting to the local conditions.

In principle, this fact means that the challenge cannot be binary and viewed as the problem of chemical versus organic. Garlic farming is a multi-objective framework where the yield, bulb quality, pest control, soil health and economic sustainability must be optimized. The reviewed literature in the proposal thus suggests an optimized balancing methodology and not complete substitution and grounds future justification in support of machine learning-based decision-support system that has the capacity to negotiate such complicated trade-offs in field specific circumstances.

Sustainability Indicators of EIA of Garlic Input Systems

Assessment of the garlic input mechanisms needs a multidimensional system of sustainability that is not reduced to mere yielding comparisons. In the proposal uploaded, it is clearly stated that sustainable garlic production cannot be evaluated by the production gains, since the intensity of pesticides, the organic management of nutrients, the health of the soil, the economic gain of the farmer, and the usability of the farmers are interlocked. It thus offers a more general evaluation framework where agronomic performance, environmental integrity, economic viability and practical practicability are looked at jointly.

Agronomically, yield, which is normally measured in quintals or tonnes per hectare, marketable bulb quality, and incidence of pest and disease are the most immediate sustainability measures. The yield is one of the main output variables that have been identified in the proposal, and so is the bulb pungency and quality, as evidenced by the content of pyruvic acid and the plant-health indices including SPAD chlorophyll values and scores of leaf-damages. These are critical variables since a system can give a high biomass but fails to give marketable qualities of the bulbs or acceptable health of crops under the commercialized conditions. Importance is also pest incidence and severity of the disease because they directly influence both the output and the future requirements of a chemical intervention.

Environmental aspect of sustainability is particularly significant in the industry of garlic where there is a trade-off between chemical and organic inputs. The proposal particularly reports that soil organic carbon (SOC) and bioefficiency ratio are the key sustainability metrics, where SOC is evaluated by the Walkley Black method and bioefficiency of the metric is the yield divided by the unit total nitrogen input. It also states that optimization of models ought to aim at reducing the pesticide load without damaging the soil health hence pesticide intensity itself must be considered a sustainability variable. Moreover, the beneficial microbial consortia, residue accumulation, and ecological stress are discussed that indicates that biodiversity, microbial well-being, and residue risk are viable environmental measurements even in cases where they are not necessarily measured in the current field research.

The economic aspect encompasses cost of cultivation, net return, and the benefit-cost performance and the overall input-use efficiency. The proposal observes that high rates of pesticides increase the cost of production, but integrated management carries out should yield a net profit increase of USD 150-200 per hectare per year. It also indicates that interventions guided by machine learning would be able to decrease the input costs by approximately 15 percent and stabilize the yield, which justifies the importance of considering sustainability by both economic efficiency and biological output.

Lastly, there are social and practical indicators, including farmer adoptability, scalability, labor needs, risk, and resilience, which cannot be eliminated. Throughout the proposal, it is mentioned several times that organic amendments are still adopted sporadically due to the fragmentation of advisory systems, staffing needs and absence of decision support systems. It means that technically superior practices might fail because they are hard to scale. This is why single-metric evaluation is not adequate. There must be a multi, multi-criteria judgment of a sustainable contribution to the garllic input system which measures productivity, environmental well-being, profitability, and viability in the real world on a single scale.

Emerging Manager Role of Data Analytics and Machine Learning in Garlic Agriculture

The new body of literature regarding the production of garlic suggests that data analytics and machine learning (ML) are gaining significance in interpreting multifaceted input-output interactions in crop management. Traditional statistics are still of fundamental importance to research in the agricultural field, and the proposal uploaded includes the descriptive statistics, correlation analysis, regression, and ANOVA as the initial levels of analytical tools to investigate the use of pesticides, application of organic fertilizers, plant-health indicators and yield variability. These measures can be useful in the summarization of field data, testing the relationships between two variables, and estimating the linear effect of key predictors including pesticide dose, rate of organic fertilizer, and SPAD chlorophyll measures. Nevertheless, the proposal also reveals that these methods prove to be inadequate in cases that are characterized by nonlinear interactions between garlic system, more than one variable interacting with each other, and dissimilar agro-climatic conditions.

In the agricultural sector and associated Allium crops, yield prediction, input optimization, pest and disease prediction and classification of management regimes are currently under investigation using ML applications. The proposed paper refers to the recent research by Vinod and Kaur (2023), who obtained an R 2 of 0.87 when predicting Allium yield by a random forest regression, yet their model could not distinguish between synthetic and organic sources of nutrients. It further mentions that research by Senapaty et al. (2024) on crop decision support showed that ML classifiers could be useful in agriculture recommendation systems, although not necessarily, yet, to the extent of field-specific garlic input balancing. These illustrations demonstrate that ML has long since left theory behind and is instead becoming useful to a greater number of practical crop-management issues.

The proposal lists some ML techniques as particularly applicable in the case of the farming of garlic, such as the Random Forest, XGBoost, Support Vector Machine-type classification logic, neural networks, such as LSTM, and ensemble models. Random Forest is allocated to underuse, optimal use or overuse practices in its proposed architecture, XGBoost is to be applied to nonlinear yield regression, LSTM with attention is proposed to predict in-season, and stacked ensemble learning is proposed to enhance predictive performance. This development is indicative of change in the nature of explanatory analytics towards predictive and prescriptive intelligence.

The key asset of ML in this sphere is its capacity to embrace the nonlinear interactions, multivariate interaction, produce site-specific suggestions, and enable real-time advisory systems. The amount of pesticide applied, the rate of organic nutrients, the soil status, pests, weather, irrigations, and the varietal reaction are different factors that influence the production of garlic simultaneously. The proposal thus proposes a decision-support pipeline whereby multi-source data are incorporated in predictive models that have the capabilities of advising the best spray and fertilizer methods under local conditions.

Simultaneously, the literature has shortcomings due to the scanty garlic-focused ML research, insufficient field level data, poor interpretability and testing, and minimal deployment by farmers. The proposal clearly states that there are no coherent datasets integrating pesticides, organic fertilizers, pest attack, crop health, and yield, and the gap is formulated as a significant obstacle on the way to the well-developed ML-based decision-support. Therefore, although ML has great potential to be sustainable toward the intensification of garlic, its full potential should be pegged on greater empirical support, interpretable modelling and eventual application in a farmer facing system.

The Case of Machine Learning Based Decision-Support Systems

The argument on machine learning-based decision-support system (DSS) in the context of garlic production is due to the apparent unsuitability of existing advisory systems. According to the uploaded proposal, the farmers in the main garlic growing districts of Maharashtra still receive generalized extension advice, according to general pesticide timetable and general NPK advice even though the field conditions in the country have significant variation based on soil type, rainfall pattern, pest pressure, irrigation regime and varietal response. These kinds of recommendations are thus not localised enough and do not incorporate the most important variables which in the real sense control crop performance, such as pesticides doses applied, the use of organic fertilisers, health of the plants, weather and soil situation. It is clearly mentioned in the proposal that farmers continue to make input decisions that are not based on data but on heuristics although site-specific schedules are necessary to coordinate the productivity, the quality of the bulbs, and soil health.

The perfect DSS of garlic should hence be based on a three-layer architecture. The input layer is supposed to absorb farm and environmental level variables such as pesticides used, organic nutrient rates, SPAD chlorophyll measurements, pest infestations, organic carbon in the soil, soil texture, rain, temperature and irrigation properties. The conceptual framework of the proposal and the architecture of the predictive-model are both supportive of such a structure, with the features being organized into the static agronomy, management practices, plant-health time-series, and climatic or remote-sensing indicators. The analytics layer must also incorporate predictive and optimization models that can classify the input regimes, predict the yield and determine pesticide and organic fertilizer combinations that maximize yield and reduce the cost of sustainability. The output layer ought to provide viable recommendations in terms of suggested sprays and fertilizer schedules, warning notices, economic briefs, and indicators of sustainability impacts.

The essence of the functions of the offered DSS is also respectively clear. First, it must be able to give yield forecast based on combined input and environmental data. Second, it ought to create pesticide prescription based on the pest pressure and crop stage. Third, it needs to accommodate the optimization of organic fertilizers by location-specific balanced nutrient. Fourth, it ought to entail sustainability scoring, especially by using indicators like soil organic carbon, and input-use efficiency. Fifth, it must conduct the cost-benefit projections that will enable farmers and extension agents to compare the practices regarding the baseline against the optimized recommendations. The FastAPI-based deployment model is precisely this logic reflected in the proposal which returns predicted yield, recommended pesticide and fertilizer schedules, an economic summary and estimated sustainability impact.

The user-centric design requirements are also important. The proposal focuses on the support of mobile/web interface, English and Marathi, offline capability using TensorFlow Lite, and streamlined recommendation screens. This is necessary since even a technically powerful DSS will not be of much consequence unless it can be made available, readable, and operable in rural settings where connectivity is low.

Lastly, such systems have a huge research translation potential. It is proposed that a tested DSS can reinforce delivery of extensions, aid policy planning on the basis of soil-health and farmer-income missions, speedy adoption of precision agriculture, and support sustainable intensification not just in garlic but in allium-related systems. In that regard, machine learning-based DSS are not just electronic devices; it is a viable way to connect the research evidence and farm-level decision-making with the policy-driven agricultural transformation.

Synthesis Of Research Gaps

The literature review has found that the knowledge base of the input management of garlic is still divided at various levels despite the increased significance of the crop of garlic as high-value crop in the face of sustainability. The first empirical gap is the lack of integrated farm-level data sets that can concurrently measure doses of pesticides, rates of organic fertilizers, pest and disease incidence, plant-health signals, yield and sustainability outcomes. Since the proposal is explicit, the current studies only tend to document only subsets of these variables. There are those that study organic amendments versus certain diseases, others that study dosage of nutrient or predictors of yield, and those that study crop-health indicators, including chlorophyll or bulb character. Nevertheless, there is still no single farm-level panel dataset available in Maharashtra that would combine pesticide, nutrient, crop-health, and environmental variables into a single analytical model. This lack greatly restricts the capability to make sound inferences regarding the capacity of chemical and organic input to impact on garlic performance in the same way.

The second group of gaps is analytical. A lot of the literature that exists is either descriptive or experimental or bivariate. Though the correlation and path-coefficient studies have provided a significant understanding on yield-related characteristics, the proposal comments that multivariate and machine learning techniques are poorly utilized in the garlic specific research. Neither synthetic nor organic nutrient sources are usually differentiated by model inputs in recent Allium prediction research and pesticide regimes are frequently assumed to be a simple binary factor instead of quantified management variables. This implies that there is yet to be done in the literature regarding rigorous analysis of chemical-organic trade-offs, interaction effects as well as optimization problems. Specifically, not many papers seek to address the core decision-maker issue of farmers, which is the identification of the input combination that will maximize production volumes and quality and minimise the pesticides load and soil health.

There are also enormous gaps in sustainability in the literature. Current research has been found to measure the success based on yield improvement only and pays less attention to the large scale environmental and long-term indicators. Several times the proposal brings forward the necessity to add the sustainability measures like the soil organic carbon, bioefficiency ratio, pesticide load, residue risk, and nutrient-use efficiency. However, such metrics are hardly ever implemented in a comparative or comprehensive manner in the existing literature. There is a weak long-term analysis of soil-health. Organic amendments are commonly demonstrated to enhance the soil resilience and only a few studies follow such modifications through several seasons and connect them with the intensity of pesticides, stress imposed on the soil by climate, and productivity in the long-term. Consequently, sustainability is weakly measured and incorporated in general garlic agronomy.

The fourth group of deficiencies is related to systems and technology. Despite the fact that there are studies in agricultural machine learning that prove crop recommendation or regional yield prediction to be feasible, the proposal observes that no functioning garlic-specific decision-support system is able to harness field-level pesticide data, organic fertilizer plans, agro-climatic circumstances, pest pressure, and sustainability targets into operational suggestions. That is, the route between field data and usable farm advice is poorly developed. This poses a great translational distance between research findings and farmer decision-making. The farmers still use blanket pesticide regimes and generic NPK guidance since there is no viable platform, to date, that can transform multifaceted agronomic ties into localized, opportune and understandable recommendations.

Lastly, there is a gap in geographic and contextual clarity of literature. The areas of the cultivation of garlic in Maharashtra are quite diverse that include the variability in rainfall, soil structure, irrigation regimes, and response to the varieties. In the proposal, Nashik, Ahmednagar, Jalgaon, Pune and Satara are singled out as separate agro-ecological environments and need to be analysed in terms of the conditions of the area. Nonetheless, there is still a lack of region-specific evidence, and much of the research available is too localized, too short-term or too little out-of-context to support large-scale decision support. Thus, existing level of knowledge is insufficient to issue site-specific garlic recommendations to Maharashtra or similar semi-arid systems in other locations.

Future Research Directions

The next steps of the research should be the creation of integrated multi-location datasets that will integrate multi-season, multi-variety, and multi-input measurements. The proposal is quite powerful along these lines as it suggests the data gathering in 120 stratified farms and managed plots in large areas producing garlic, as well as using weather, soil, and historical data. These datasets are crucial since they would allow comparative analysis between irrigation systems, varieties and agro-climatic zones instead of addressing one or more management factor separately.

Second, the future generation of the literature ought to go beyond single-specified correlation analysis to joint causal and predictive research designs. Correlation is helpful to draw patterns, but it should be accompanied by experimental and model-based research, which explains the effects of interactions, threshold behavior and the causeways. The combination of field surveys, randomized block experiment, regression, classification, and optimization provides an excellent model of this transition in the proposal.

Thirdly, sustainability-oriented model development is highly required. The future models are not supposed to maximize yield only. Rather, they ought to view yield, pesticide burden, soil organic carbon and input-use efficiency as concurrent goals. The application of genetic algorithms in the proposal to determine the Pareto-optimal combination of pesticides and organic fertilizers is particularly applicable in this case, as it is aimed at the actual trade-off structure of garlic farming.

Fourth, remote sensing and IoT should be further integrated in the future. It is already envisaged in the proposal that weather APIs, Sentinel-2 imagery, soil and plant-health indicators, and real-time alerts are to be used in the proposal. A further extension of this strategy by crop imaging, automated pest surveillance, and sensor-based monitoring would go a long way in enhancing predictive accuracy and time responsiveness.

Fifth, field validation with farmers must be part of all the development of DSSs. The methodological significance of the plan in the proposal to make comparisons between volunteer farms based on app-recommended farms with control farms based on conventional advisories is that it would change the question of the technical feasibility to the agronomic usefulness and social usefulness. The use of participatory validation then should be the norm in subsequent research on garlic DSS.

Lastly, there are needs to have stronger policy and extension linkages. Evidence that can inform soil-health missions, organic-input incentives, and precision extension services should be generated in future research. The policy orientation of the proposal including the connection of the results of the models to the Soil Health Card Scheme, increase of the income, and scalable Allium advisories demonstrates the way in which the research can be converted into the institutional and extension effect.

Conclusion

This review illustrates how sustainable management of garlic production is based on balanced management of inputs. Chemical or organic fertilizers cannot be singly treated as their effectiveness in inhibiting pests, the quality of bulbs, and the well-being of the soil is affected by their interplay in a particular environmental and management scenario. The evidence reviewed recommends that the input classes are not illegitimately agronomically applicable, however, their application needs to be optimized as opposed to being generalized.

The core message of this review is that evidence-based balancing rather than simplistic input substitution or treatment is the future of garlic agronomy. The literature is far too divided to be able to respond to this challenge in a satisfactory way when farmers require empirical information about how to overcome trade-offs between productivity, environmental sustainability, and profitability.

DSSs that are supported by machine learning, therefore, cannot be considered as optional digital extensions. They are becoming essential in the management of the complexity of the production systems of garlic, especially in heterogeneous regions like Maharashtra whereby the soil, weather, pest pressure, and management conditions differ remarkably between places. These systems combine field data, predictive analytics, sustainability metrics, and farmer-focused delivery, which provides the best way to enter the least promising avenue of scientifically based, regionally specific, and scalable garlic advisory services.

Table 1: Summary Of Reviewed Studies on Chemical Pesticides in Garlic

Authors/Year	Study Focus	Crop/Context	Chemical or Protective Input	Main Finding	Limitation / Gap
Hardiansyah et al., 2020	Garlic-based extract as pest repellent	Rice-eating bird pest context; plant-derived pesticide relevance	Garlic extract spray (5% allicin concentration)	Reduced bird attacks by about 70%, suggesting pesticidal potential of garlic-derived compounds	Did not link treatment with garlic yield metrics; no multivariate analysis
Srinivas and Lawande, 2004	Pest pressure dynamics	Onion used as a related Allium reference	Indirect pest-management strategy through planting date	Delayed planting reduced *Thrips tabaci* pressure by about 30%	Not a garlic-specific pesticide dose study
Proposal field framework	Garlic pest suppression in Maharashtra	Garlic varieties G-41, G-50, G-189	Deltamethrin 2.8 EC, Fipronil 5 SC, Profenofos 50 EC, Spinosad 45 SC	Identified as key chemical pesticides to be logged by concentration, spray volume, and timing	No existing unified dataset yet to compare their dose-response effects
Proposal significance section	Current pesticide-use imbalance	Maharashtra garlic systems	Synthetic pesticide dependence	Overuse linked with residue accumulation, higher costs, pest resistance, and ecological stress	Evidence remains fragmented across studies
Proposal problem statement	Advisory gap	Major garlic-growing districts of Maharashtra	Generalized spray schedules	Blanket recommendations fail to account for soil, pest pressure, and varietal differences	No site-specific optimized pesticide scheduling model

Table 2: Summary Of Reviewed Studies on Organic Fertilizers / INM In Garlic

Authors/Year	Organic / INM Treatment	Comparison	Main Agronomic Outcome	Soil / Sustainability Outcome	Limitation
Prajapati et	Vermicompos	Chemical	Purple	Indicates	Did not

al., 2020	t, neem cake, biofertilizers	fertilizer alone	blotch severity reduced by about 38%; yield increased by about 15 q/ha	strong potential of organic amendments in disease management and yield support	analyze pesticide-organic trade-offs jointly
NCBI PMC, 2021	Feature-specific nutrient dosage; phosphorus-enriched fertigation	Standard nutrient regime	Improved bulb quality and nutrient-specific response	Showed importance of dosage-sensitive nutrient management	Did not include pest incidence or predictive analytics
Proposal scope section	19:19:19 water-soluble NPK at 30, 45, 60 DAP plus INM	Stand-alone chemical input regime	Proposed as optimized integrated nutrient package for garlic	Includes vermicompost 5 t/ha, neem cake 500 kg/ha, Azospirillum 10 kg/ha, PSB 10 kg/ha	Still proposed; requires empirical validation
Proposal significance section	Combined vermicompost + neem cake	Conventional practice	Supported about 0.8 t/ha yield increment	Raised SOC from 0.4% to 0.7%; improved water-holding capacity by 12%	Adoption remains sporadic
Proposal objectives / hypotheses	Integrated organic fertilizer use	Non-integrated practice	Expected positive correlation with yield and plant health	Expected improvement in soil health indicators independent of pesticide levels	Needs farm-level dataset and validation

Table 3: Sustainability Metrics Used Across the Literature

Category	**Metric**	**Measurement / Unit**	**Purpose**	**Relevance**
Agronomic	Bulb quality / pungency	Sulfuric acid (μmol/g)	Measures market quality and consumer value	Linked with balanced inputs and improved bulb quality
Agronomic	Pest incidence	Thrips per leaflet; % leaf area damaged	Measures effectiveness of crop protection	Useful for pesticide optimization
Plant Health	SPAD chlorophyll	SPAD meter readings	Proxy for nutritional status and vigor	Important intermediate variable
Environmental	Soil organic carbon	% via Walkley–Black method	Key long-term soil health indicator	Central sustainability metric in proposal
Environmental	Bioefficiency ratio	Yield per unit total N applied	Reflects nutrient-use efficiency	Useful in comparing INM

				systems
Environmental	Pesticide load / intensity	kg ai/ha or cumulative ai	Indicates chemical pressure and residue risk	Important for trade-off analysis
Economic	Input cost differential	USD/ha	Measures economic efficiency of optimized recommendations	Proposal targets cost reduction
Economic	Net profitability gain	USD/ha	Assesses return from model-driven management	Proposal estimates USD 150–200/ha gain
Social / Practical	Farmer satisfaction	Likert scale	Measures adoption potential of DSS	Included in field validation protocol

Table 4: Comparison Of Conventional Statistical Vs. ML Approaches in Garlic / Agriculture Studies

Approach / Model	**Category**	**Application**	**Strengths**	**Limitations**	**Relevance to Proposed Study**
Regression	Statistical	Correlation and interpretable relationships	Simple, interpretable, and benchmark model	Limited handling of nonlinear relationships	Used as a benchmark model
Random Forest	ML	Classification of underuse / optimal / overuse regimes	Handles interactions and nonlinearity effectively	Lower interpretability than simple models	Central to proposed classification pipeline
XGBoost	ML	Yield prediction and nonlinear regression	High predictive performance	Requires careful tuning	Central to proposed predictive modeling
LSTM	ML	In-season time-series forecasting	Captures temporal variation	Data-intensive	Proposed for weekly yield trajectory prediction
Stacked Ensemble	ML	Combining top-performing models	Improves accuracy and robustness	More complex deployment	Proposed for maximizing R^2 and minimizing RMSE
SHAP-Supported Models	Explainable ML	Feature contribution analysis	Improves interpretability	Additional computational cost	Important for farmer trust and advisory clarity

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