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The Economic Impact and Integrated Management Strategies against *Tomato Yellow Leaf Curl Virus* (TYLCV): A Review

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ABSTRACT

The plants viruses have been examined to study the economic losses associated with agricultural crops and the viruses that represent a focus of attention of this study, in particular the *Tomato Yellow leaf curl virus* (TYLCV) and its impact on tomato productivity in Iraq. A study highlights the destroy produced by this virus, which can reach up to 100% in severe cases. This review aims to provide a comprehensive overview of the economic impact of TYLCV on tomato productivity in Iraq and to discuss integrated management strategies. It addresses the significant yield losses, which can be up to 100% in severe cases. In addition, it examines the effect of the virus on the chemical composition of fruit and reduces both nutritional value and marketing. The study emphasizes that controlling plant viruses requires integrated strategies, including development of resistant cultivars, the use of chemical, biological and agronomic control measures within an integrated management framework has been stressed as the best way to control plant viruses. It also underscores the need for enhanced scientific research and for improving farmers' awareness. Additionally, it explores the effects of plant viruses on the chemical composition of associated plants, such as some mineral elements and plant hormones and how the plant responses resulting from the interaction of the host plant and the virus can lead to the decay of crop quality. Virus management strategies, including resistant cultivars, agricultural control methods such as the use of biological control methods and nanotechnology, in some limited cases, chemical pesticides used in a responsible manner, are discussed. Overall, this review highlights the urgent need for robust, integrated management strategies to mitigate the devastating effects of TYLCV and enhance the sustainability of tomato production in Iraq.

Key words: Genetic engineering, Integrated management strategies, Nanotechnology, Plant viruses, *Tomato yellow leaf curl virus* (TYLCV).

Plant viruses are one of the most important biotic constraints to crop productivity and quality worldwide and constitute major threats to food security and agricultural sustainability (Singh *et al.,* 2023). Such viruses result in significant economic loss for farmers and consumers due to decreased yield and quality and increased control expenses (Strange and Scott, 2005; Kazancoglu *et al.,* 2024). This analytical study is estimated to be the economic effect of plant virus, especially *Tomato yellow leaf curl virus* (TYLCV) in Iraq. One of the most universal and destructive viral diseases in the tomato crops in the region is TYLCV (Al-Abedy *et al.,* 2018b; Hassan *et al.,* 2022).

According to Hassan *et al.* (2022), TYLCV causes a major reduction in the productivity of tomatoes, with loss potentially reduced up to 100% depending on the severity of the infection and the types of cultivar of tomato, development stage of the plant when infected and environmental conditions. TYLCV has also caused up to 80% or more crop loss in tomato (Jubair *et al.,* 2020; Karem *et al.,* 2023a). In addition, viruses in plants induce alteration in chemical properties that lowers the nutritional and commercial value of plant products, thus reducing the overall quality. Al-Shammari *et al.* (2023a) and Karem *et al.* (2023a) showed that TYLCV and *Cucumber Mosaic Virus* (CMV) infection results in altered contents of essential mineral elements, vitamins and bioactive compounds in tomato fruits, including lycopene. These changes in chemical composition can affect taste, aroma and appearance, decreasing the consumers' interest and reducing market value of the commodity.

Viruses control measures have to be applied through the use of the appropriate insecticides to manage the insect vector, *e.g*., whitefly (*Bemisia tabaci*), removal of the infected control plants, as well as wide use of protective netting to cover seedlings. These systems also increase the overall production costs, mainly higher pest management costs (AL-Abedy *et al.,* 2021a). The utilization of biological and

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nanotechnology-based control measures to control virus spread, to minimize dependency on chemical pesticides and minimize detrimental environmental impact has been investigated in multiple studies (Hassan *et al.,* 2020). Virus infections may also prevent the export of agricultural products, constraining farmers' access to global markets. This is a challenge in the export of products as such conditions act as trade barriers (FAO, 2017) where, In case of Imported markets, many require a health certificate certifying the product to be free of viral diseases which makes life tougher for farmers from the regions that are still fighting with that viral threat.

The control of plant viruses is difficult due to their high adaptability and genetic variability, which makes it challenging to develop resistant cultivars (Luo *et al.,* 2023). Al-Abedy *et al.* (2018) and Al-Abedy *et al.* (2021e) reported that genetic diversity in isolates of TYLCV has been enabled by some authors (2018, 2021) to overcome resistance breaking of newly cultivated resistant cultivars in Iraq. This requires continuous breeding and the introduction of new resistant cultivars. Moreover, certain plant viruses have a wide host range and can infect numerous plant species, further contributing to their potential for dissemination. However, this wide host range phenomenon allows migration of viruses from cultivated crops to weeds and wild types of plant species which complicates the control of such viruses (Ahlawat, 1997; Zewdu *et al.,* 2023).

Many viruses rely on insects to shuffle between plants, complicating their management. Insect vectors are generally managed with insecticides, resulting in detrimental impact on the ecosystem and human health. It also adds the issue of climate change as a facilitator to the spread of many viruses and their insect vectors, making things worse and yet another challenge. Moreover, changes in precipitation patterns and increase in temperatures may provide mechanisms to some insect vectors to expand their distributional ranges enhancing virus transmission events (Trebicki, 2020). These interwoven variables illustrate the need for adaptive strategies that can not only address viral diseases, but also larger organic and climate factors that enable their spread. Integrated approach based management will be needed by balancing insect control, environmental protection, sustainable agricultural practices to overcome these emerging issues.

In general, an agricultural basis, plant viruses that cost farmers and consumers a great deal of money. However, to counter such threats integrated management including modern breeding and genetic engineering for producing resistant cultivars is needed. It is equally important to implement comprehensive control measures that integrate chemical, biological and agronomic approaches. Along with that finding, strengthening scientific research is also important preferences to understand the mechanisms of viral infections and the methods of effective and sustainable control. Moreover, it is so important to increase preventive action awareness among farmers and quick action on onset of symptoms is crucial for proper management (Torrance *et al.,* 2020; AL-Abedy, 2021a; AL-Abedy *et al.*, 2021b). Moreover, these virus spreaders should be prevented from moving to new fields by those making policies, while also helping researchers work to create ways to improve agricultural practices.

The viral impact on some chemical components of plants

Viruses are among biological factors that significantly affect physical and chemical processes in plants, which negatively affect their growth, development and productivity. Viral infection triggers a series of complex metabolic changes, which in turn interferes with delicate chemical balance that plants maintain under normal conditions. The current work is a detailed review that makes an effort to collect the existing scientific evidence regarding the relationship between viruses and the changes that they elicit in the element and hormone phytochemistry of the infected plants, as well as the possible consequences that could be expected from these changes.

Viral infection interferes with the uptake, transport and allocation of mineral elements within the plant-processes that are vital for normal growth and metabolism. Viruses have been also found to affect root uptake of essential nutrients from soil by mediating transport functions on cell membranes as well as reducing gene expression directed to such processes (AL-Abedy *et al.,* 2019; AL-Abedy *et al.,* 2020). Moreover, viruses interfere with the transport of these components through the vascular tissues (xylem and phloem), resulting in an uneven distribution of metabolites throughout plant tissues and their localized accumulation at the expense of others (Ganusova *et al.,* 2017).

For example, Hassan *et al.* (2022) and Karem *et al.* (2023b), the relationship between the TYLCV and mineral content in tomatoes was explored. In both leaves and fruits, it established that viral infection induces drastic changes in the concentrations of the leaf-essential elements nitrogen, phosphorous, potassium, calcium and magnesium. Such changes in mineral element contents were associated with the impaired physiological functions such as photosynthesis and protein synthesis, which was detrimental to growth and productivity. In addition, viruses can affect complex enzymatic processes responsible for metabolizing mineral elements, which further complicated bio-chemical effects. Which accumulates of some toxic compounds or decline in essential compounds (Tripathi *et al.,* 2022). Moreover, Al-Shammari *et al.* (2023b) investigated the impact of Cucumber Mosaic Virus (CMV) on the chemical composition of tomatoes. Their observations showed that the virus not only affects minerals, but also vitamins, emphasizing the notion that viruses can impact a wide variety of biochemical compounds within the plant.

Aside from disrupting mineral elements, viruses hijack the sensitive hormonal harmony in plants, highly vital for

regulating growth, development and responses to changing environmental conditions (Singhal *et al.,* 2023). Plant hormones, such as auxins, cytokinins, gibberellins, ethylene, abscisic acid, salicylic acid and jasmonic acid, are the MVPs (Major Vital Plant Processes) when it comes to regulating a wide variety of physiological processes. We're talking cell division, elongation, differentiation, flower and fruit formation and even how plants respond to both living and non-living stresses (Ali and Baloch, 2020). When a virus hits, it can shake up hormone levels big time by messing with how they're made, moved around, distributed and broken down (Medina-Puche *et al.,* 2020). Al-Abedy *et al.* (2021b) revealed that TYLCV infection disrupts with hormone levels in tomato plants causing aberrant growth and development. These hormonal changes can lead to telltale symptoms of a viral infection-like stunted growth, curling leaves and deformed fruits-which all indicate a hormonal imbalance messing with the plant's normal processes.

Apart from influencing the mineral elements, plant viruses also greatly affect the delicate hormonal balance of plants required for regulation of growth, development and reactions to diverse environmental conditions (Singhal *et al.,* 2023). Auxins, gibberellins, cytokinins, ethylene, salicylic acid, abscisic acid and jasmonic acid are the most plant hormones that help modulate different physiological processes, mainly cell division, elongation, differentiation, flowering and fruiting processes, in addition to responses to biotic and abiotic stresses (Ali and Baloch, 2020). These changes could be assisted by virus infections that result drastic deregulation in the levels of plant hormones due to the bio molecular pathways affected, where the biosynthesis, transport, distribution and metabolism are disturbed by virus infections at different levels of the plant growth (Lozano-Durán *et al.,* 2011). It has found that TYLCV infection has a strong influence on hormone levels and changes the growth and development of plants (Al-Abedy *et al.,* 2021b). In addition to these physiological changes, virus-related infections can give specific changes in hormonal profiles that can significantly affect plant growth and development by disturbing the hormonal homeostasis, resultant in distinct symptoms that variety from stunting and curling of pant leaves to structural abnormalities of fruits.

Changes in the chemical composition of plants, whether it's the mineral elements or plant hormones can seriously harm crop quality and productivity. These shifts can lower the nutritional value of agricultural products due to a drop in essential minerals, vitamins and biologically active compounds that humans need for good health (El-Ramady *et al.,* 2022). Additionally, disruption of chemical balance can reduce the resistance of the plant to other diseases and environmental conditions that have adverse influences, which makes the plant more susceptible to pests and other diseases (Aljuaifari *et al.,* 2019). Thus, knowing how viruses influence the diversity of plant chemical compounds is fundamental to the establishment of preventions and control measures. These strategies are usage of virus-resistant plant varieties bred through traditional breeding methods and modern biotech, implementation of integrated pest management that combines good agricultural practices with a mix of biological and targeted chemical controls and better soil nutrient management to improve plant health and its resilience to viral diseases (Tanda, 2024).

The impact of plant viruses on the nutritional value and chemical composition of plants

One of the most important factors that determine the nutritional and market value of agricultural crops is its quality and viruses have great effect on this quality (Al-Sharmani *et al.,* 2019). Viral infections disrupt several physiological and biochemical changes in the plant body that lead to a decline in crop quality (Jiang and Zhou, 2023). The impact of plant viruses on crop quality determined by its nutritional value and chemical composition will be explored in this study.

There are various approaches in which viruses affect the quality of crops. First, viruses can lower the levels of some essential nutrients in crops, such as vitamins and minerals and proteins. For instance, Karem *et al.* (2023a) indicated that the TYLCV infection significantly affected lycopene and some vitamins in the tomato fruits. Similarly, Hassan *et al.* (2022). However, indicated that TYLCV infection altered tomato plants' mineral profiles, with implications for the nutritional quality of the crops and health of the consumers In the second aspect, viruses may modify the chemical composition of crops, by altering the levels of secondary metabolites (like antioxidants and phenolic compounds), which are crucial to perform their functions in preventing cells from oxidative stress through the scavenging of free radicals (Mangal *et al.,* 2021). This probably occurs *via* several biochemical pathways that further affect sensory characteristics of the crops, such as taste, aroma and color, which also directly impact the sale of crops and ultimate consumer adoption.

A study by Al-Shammari *et al.* (2023a) shows that infection with the Cucumber Mosaic Virus (CMV) negatively affected the tomato chemical composition, including the contents of essential vitamins and minerals. Third, virus infections can change the external appearance of crops and make them less attractive to consumers. For example, viruses in plants are responsible for stains and deformity of the size of leaves or fruits and small crops. These visual changes reduce the quality and market value of crops for consumers, who just like to buy healthy goods (Alhissnawi *et al.,* 2024).

Viruses disrupting intra-plant chemical homeostasis

Plant viruses are one of the main factors contributing to vital and chemical processes in plants. Infected with the virus, plants that are not sick do not grow well because viral infections interfere with the balance of chemicals, thus affecting its growth, development and productivity

(Jiang and Zhou, 2023) Hence, this review aims to dissect pathways leading to breakdown of chemical equilibrium in virus-infected plants, along with implications of such disequilibrium. Viruses meddle with the plant's chemical balance in various clever methods.

First, Viruses can target processes impacting the absorption, transport and distribution of mineral nutrients in the host plant. For example, can impair the ability of roots to take up nutrients from the soil, or disrupt the flow of those nutrients through the vascular system. In this regard, Hassan *et al.* (2022) and Karem *et al.* (2023b) studies effects of TYLCV on mineral concentration in tomato. Leaves and fruit infected turned out to have significantly different concentrations of important plant elements, such as nitrogen, phosphorus, potassium, calcium and magnesium, to name but a few. Such disturbances may lead to nutrient deficits or imbalances, hindering essential physiological processes and decreasing the general health and productivity of plants.

Second, the virus can interfere with hormonal balance in plants, which play an important role in growth, development and regulatory reactions from different environmental conditions. Viral infections can change the level of plant hormones, affecting some of physiological processes. AL-Abedy *et al.* (2021b) study showed that infection with tomato - TYLCV had a significant impact on the hormone content of tomato plants, resulting in change in growth and development, as well as the presence of symptoms such as curling and stunting in infected plants.

Changes in the chemical balance of plants lead to many negative effects, including a reduction in photosynthesis rates, reduced vegetation growth, reduction in the production of fruit and increased sensitivity to other diseases and pests (Saqib *et al.,* 2022). In addition, shifts in chemical composition may affect crop quality, thereby decreasing their nutritional and market value. Examples of this include the studies done by Al-Shammari *et al.* (2023b) showed that infection with *Cucumber Mosaic Virus* (CMV) changes the chemical composition of tomatoes, reducing the levels of important minerals, vitamins, carbohydrates and enzymes. Since the electronic mismatch of viruses can change the chemical composition of plants, it is essential to know the mechanisms by which viruses alter the chemical balance of them economically important plants to save them from disease. These strategies include using resistant crop varieties, implementing integrated pest management practices, improving soil nutrient management and adopting clean farming techniques (Ragunathan and Divakar, 2020).

The role of mineral elements and plant hormones in plant resistance to viral infections

The plant resistance to the viral infection is a multicomplex process of interactions between the various internal and external elements. Which calls for a comprehensive understanding of the diverse defense mechanisms that plants possess (Roychowdhury *et al.,* 2025). These defense mechanisms consists of innate immunity (composed of pre-existing physical and chemical barriers) and acquired immunity that is elicited in response to infection (Solanki *et al.,* 2021). A highly complex molecular signaling network modulates these immune responses, where hormonal pathways and mineral nutrients emerge as key positive and negative modulators of the interaction outcome between plants and viruses (Pieterse *et al.,* 2012). In this mini-review we highlight the role of various mineral elements and plant hormones on plant resistance against viruses and provide the molecular framework of the complex interplay between them.

Several interrelated mechanisms in which metallic elements participate significantly contribute to increasing plant resistance to viral infections. They serve as cofactors for important defense-related enzymes, modulate gene expression and stabilize structures (Tripathi *et al.,* 2022).

First, certain mineral elements are known to activate key enzymes that aid plant defense against viral infections. These include antioxidant enzymes that counteract the oxidative stress of infection. Zinc, for instance, is a cofactor for the enzyme superoxide dismutase (SOD). This enzyme is responsible for the conversion of superoxide radicals (O_2^-) to hydrogen peroxide (H_2O_2), a crucial signal molecule, which plays a significant role in the plant defense strategy (Mishra and Sharma, 2019). Manganese (Mn) and Cu also required for activation of other antioxidant enzymes such as catalase (CAT) and peroxidase (POD) keep detoxifying H_2O_2 and reduce oxidative damage due to viral stresses (Singh *et al.,* 2023). Viral infections frequently cause an overproduction of reactive oxygen species (ROS) due to the disruption of photosynthesis, as well as the activation of alternative metabolic pathways. These ROS can damage cellular structures such as DNA, proteins and lipids. By activating antioxidant defense enzymes, mineral nutrients play an important role in reducing the ROS level, protecting cellular integrity, maintaining physical functions and limiting viruses spread into plant tissue (Sharma *et al.,* 2019; Kamaluddin *et al.,* 2021).

Second, some mineral elements may increase the production of defensive compounds in plants, such as phytoalexins, which act as natural antibiotics to disrupt viral replication and limit their spread (Al-Shugeairy *et al.,* 2021). For example, calcium (Ca) has been shown to play an important role in regulating signaling pathways leading to the production of phytoalexin biosynthesis in virus -infected plants (Then *et al.,* 2021). Calcium acts as a second messenger in signaling pathways during plant defense. A rise in intracellular calcium concentrations triggers a series of downstream events involving protein kinases and transcription factors that modulate the expression of phytoalexin biosynthesis genes (Mahdi *et al.,* 2020). Further, some mineral elements contribute to the strength of cell walls, thus minimizing the possibility of viruses entering the plant cells (Singhal *et al.,* 2023). For example, calcium

strengthens cell walls through cross-linking of pectins, which are the main components of plant cell walls (Mnati *et al.,* 2021). Additionally, potassium (K) and phosphorus (P) are critical in enhancing systemic acquired resistance (SAR), a durable immune response providing broad immunity against various pathogens, including viruses (AL-Abedy *et al*., 2021e; Thepbandit and Athinuwa, 2024).

Assessing the efficiency and economics of controlling plant viruses

Plant virus is one of the main challenges which leads to economic losses in agricultural production all over the world, enough to cause damage to recovery and quality. As food security and agricultural stability take on ever greater importance, so the need to develop and apply effective strategies for managing plant viruses has become more acute.

The study facility deals with the concept of integrated strategies for plant virus management and evaluates their efficiency and financial effects based on available scientific evidence. Integrated virus management strategies depend on a combination of many approaches and technologies, which are directed at the virus, its insect vectors and environmental conditions that facilitate the spread. These strategies require the use of virus-resistant cultivars, adoption of sound agronomic practices, applications of biological control methods and responsible and limited use of chemical pesticides. Methods are selected and applied based on local conditions, characteristics of the virus, insect vector and target crop.

They are several elements of integrated plant virus management strategies.

Use of resistant cultivars

However, the use of virus resistant cultivars is regarded as one of the most effective and sustainable strategies to mitigate crop loss by virus infection. Most of the major plants viruses have resistant cultivars, so farmers can select those compatible with their conditions. Torrance *et al.* (2020) explored the natural resistance of some wild potato species against *Potato virus Y* (PVY), thus, it could potentially yield better virus resistant potato cultivars.

Cultural control practices

These measures form part of a broader range of integrated pest management (IPM) strategies that can include practices that reduce the spread of plant virus and their vectors. Essential tactics include eliminating infected plants, controlling weeds that serve as alternate hosts of the viruses, planting unrelated crops in a given area to disrupt the life cycles of the viruses and vectors and using certified disease-free seeds. Such measures are essential to minimizing sources of infection and preventing the establishment and spread of viral diseases in crop zones.

Biological control

Biological control uses beneficial microorganisms or natural products to restrain the virus of plant or their insects vector. Parasite Insect Vector is a type of bacteria or fungus, for instance, that can infect and kill the vector reducing the population and as a result, the transfer of virus. Few of previous studies discussed some other *Trichoderma* spp. which are being explored for their potential in controlling TYLCV, along with soil-borne pathogenic fungi and various nanomaterials, as highlighted by Al-Salami *et al*. (2019); Al-Abedy *et al*. (2021b); AL-Abedy *et al*. (2021d); Mahmood and Al-Abedy (2021).

Chemical control

Under some conditions, the use of chemical pesticides may be necessary to control the insect vector responsible for transferring the plant virus. However, chemical control should be used with restraint and responsible, with its environmental impact and possible risks to human health (Neamah, 2020; Al-Abedy *et al.,* 2021d; Odeh *et al.,* 2021).

Evaluating the effectiveness of integrated strategies for controlling plant viruses requires considering several key factors, including.

- **Reducing losses**
- Integrated strategy should effectively reduce the damage caused by viral infections, such as low yield and worsened quality. This is important to ensure food security and maintain financial stability for farmers.
- **Sustainability**
- The strategy should be environmentally and financially durable, which means that it should not create significant negative effects on the environment or can cause sufficient increase in production costs. Long-lasting viability is necessary for your continuous adoption.
- **Social acceptance**
- Strategy should be acceptable for farmers, consumers and regulatory bodies. Getting trust and cooperation from all stakeholders is important to ensure extensive implementation and compliance.

By addressing these factors, integrated viral management strategies can achieve their goals by balanced organic, economic and social idea.

Analyzing the economic effect of integrated plant virus management strategies involves weighing the costs of implementation-for example, the implementation of resistant cultivars, cultural and biological control measures and when necessary when using chemical pesticides-they provide benefits (Muteab and Al-Abedy, 2025). These benefits include an increase in crop, improvement in return quality and low damage due to viral infections. Cost-profit analysis aids in practical financial evaluation of these strategies, as well as the real assessment of trading price stability of such strategies, ultimately helping make an informed decision about the strategies that maximize productivity and profitability and reduce the long-term risk of crop health and environmental stability. Due to the complexity of plant virus problems, integrated strategies

are considered the most effective and sustainable way to reduce losses caused by these diseases. Farmers can promote plant health and contribute to environmental sustainability while reducing their reliance on chemical pesticides by employing a variety of methods and technologies.

Agricultural challenges and the advancement of plant virus management

Modern agricultural facilities are facing increasing challenges due to the widespread emergence of viruses, causing significant economic losses and a serious threat to global food security (Reshma *et al.,* 2022). In response, there has been a remarkable change in plant virus management - traditional methods up to advanced technologies such as genetic technology and nanotechnology (Mishra *et al.,* 2025). The purpose of this presentation is to highlight the development of plant virus control strategies, with the mechanisms behind each approach, their efficiency and focus on practical applications in the field.

CONCLUSION

This analytical study is aimed to show the economic and biological importance of plant viruses especially TYLCV in Iraq. As a result, this virus poses a serious threat to agricultural production, causing social and economic losses, as well as decreased quality of the crops. It also emphasizes the importance of understanding molecular and chemical mechanisms affected by viral infection and their impact on the nutritional value and marketability of agricultural products. Such insight is important to good management practices and sustainable agriculture.

To address the economic and biological challenges posed by plant viruses, there is an urgent need to develop integrated strategies for virus management. These strategies must include the use of resistant varieties, agronomic and biological control methods, complemented with chemical pesticide applications, if necessary, but in a responsible and cautious manner. Governments and international organizations must support research and development in this critical part, comprising the exploration of advanced technologies such as genetic engineering and nanotechnology. Farmers must be educated on the information on the need for preventive steps and how to interfere as soon as symptoms appear and training and support to adopt best agricultural practices. Finally, the efficiency and effects of these integrated strategies need to be routinely assessed to confirm their long-term and effective sustainability in the defense of agricultural crops while helping food security and agricultural sustainability.

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Informed consent

Not applicable. This study is a review of existing literature and did not involve any human participants or animal subjects.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No funding or sponsorship influenced the design of the study; collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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