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Review of the main diseases of *Solanum lycopersicum* and methods of chemical control of pathogens

Liliia Havryliuk*
Doctor of Philosophy, Senior Researcher
Institute of Agroecology and Nature Management of the National Academy of Sciences of Ukraine
03143, 12 Metrolohichna Str., Kyiv, Ukraine
https://orcid.org/0000-0001-6901-0766

Iryna Beznosko
PhD in Biological Sciences, Senior Researcher
Institute of Agroecology and Nature Management of the National Academy of Sciences of Ukraine
03143, 12 Metrolohichna Str., Kyiv, Ukraine
https://orcid.org/0000-0002-2217-5165

Danylo Humennyi
Postgraduate Student
Institute of Agroecology and Nature Management of the National Academy of Sciences of Ukraine
03143, 12 Metrolohichna Str., Kyiv, Ukraine
https://orcid.org/0009-0009-2936-4506

Dmytro Gentosh
PhD in Agriculture
National University of Life and Environmental Sciences of Ukraine
03041, 13 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0001-8647-7843

Olena Bashta
PhD in Biological Sciences
National University of Life and Environmental Sciences of Ukraine
03041, 13 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0003-4682-1595

Abstract. This article overviews the major diseases affecting tomato plants (*Solanum lycopersicum*), caused by viral, bacterial, and phytopathogenic microorganisms. Pathogenic microorganisms parasitising tomato plants lead to significant crop losses in agricultural production, reducing the quality of the produce. The study aimed to investigate the impact of microorganisms on tomato plants, the extent of their harmful effects, and methods of controlling disease pathogens. It has been established that the primary diseases of tomato plants are caused by fungi of the genera *Fusarium* (fusarium wilt), *Phytophthora* (late blight), *Botrytis* (grey mould), and *Alternaria* (early blight); viruses such as *tomato spotted wilt virus* and *tomato yellow leaf curl virus*; and bacteria such as *Ascochyta*

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*Corresponding author

cucumis (bacterial canker of tomatoes) and *Xanthomonas vesicatoria* (bacterial spot). Agricultural chemicals are recognised as an essential component in pest and disease management, and the primary means of combating plant diseases include chemical substances such as prochloraz, thiabendazole, propiconazole, carbendazim, benomyl, thiophanate, fuberidazole, and others. Systemic fungicides are crucial in controlling various diseases and exhibit beneficial physiological or growth-stimulating effects on plants, including delaying leaf senescence and increasing chlorophyll content. It has been observed that fungicides (chemical groups: strobilurin and carboxamide) are effective in combating early blight, while the primary strategy for controlling grey mould involves chemical management through the use of synthetic fungicides such as quinone inhibitors, benzimidazoles, carbamates, phenylpyrroles, and succinate dehydrogenase inhibitors. Reviewing diseases and chemical control methods for pathogens is highly valuable for agricultural applications. The practical significance of this research lies in its ability to help agricultural producers manage their crops effectively and maintain fruit quality. Knowledge of the major diseases affecting tomatoes enables the timely identification of symptoms and the implementation of appropriate preventive and treatment measures

Keywords: digital technologies; electronic systems; accounting automation; economic efficiency; audit and control

INTRODUCTION

Knowledge of the diseases that can affect plant health and crop yield is essential for taking timely measures to prevent and control them. The use of fungicides and other chemical agents can be effective in combating diseases and preserving the harvest, particularly for tomatoes. It is important to continually update knowledge on new control methods and protective measures to safeguard agricultural crops from pests. Diseases of *Solanum lycopersicum*, caused by pathogenic microorganisms, are among the most dangerous biotic stresses, negatively impacting yield and causing significant damage in various countries, including Ukraine. Microscopic fungi, in particular, lead to substantial crop losses by parasitising plants, significantly reducing both the quality and quantity of agricultural produce.

Phytopathogens of *Solanum lycopersicum* produce toxins (mycotoxins), which pose a serious threat to human and animal health, as they can cause diseases and poisoning. This can lead to conditions such as aflatoxicosis and ochratoxicosis. To prevent widespread illness caused by micromycetes, it is essential to implement control and preventive measures, including the selection of resistant varieties, agronomic practices, fungicidal treatments, monitoring, control, chemical and biological remediation, and further research (Suresh *et al.*, 2022). Researchers such as A. El-Nagar *et al*. (2020), Z. Maskova *et al*. (2022) and A. Slama *et al*. (2022) have concluded that pathogenic fungi are the most prevalent microorganisms causing plant diseases, affecting up to 80% of crops. This conclusion highlights the importance of studying and controlling these microorganisms to ensure plant health and productivity. These research findings may prove valuable in developing strategies to combat phytopathogenic micromycetes and improve disease management in agriculture.

M. Attia *et al*. (2020) investigated that tomato plants can be affected by several disease pathogens, which can develop on all vegetative organs of the plants. They also analysed the antagonistic activity of *A. solani* and recorded the plant's metabolic resistance indicators in response to induced systemic resistance. The results showed that the isolates reduced disease development in the plant by 13%, with the plant's protective capacity reaching 84.3%. Y. Nehela *et al*. (2021), while studying the protective potential of benzoic acid and two of its hydroxylated derivatives (hydroxybenzoic acid and protocatechuic acid) against the *Alternaria* pathogen, found that all the compounds significantly reduced pathogen development. Hydroxylated derivatives and benzoic acid enhanced vegetative growth and yield. These findings highlight the physiological and biochemical mechanisms they possess. Researchers S. Panno *et al*. (2021) noted that, due to the genetic characteristics of tomatoes, they are susceptible to numerous pathogens (bacterial, fungal, viral, and phytoplasmal). Therefore, recognising symptoms and understanding the spread of diseases, along with early detection methods for pathogens, are key prerequisites for successful disease treatment. The scale and pace of tomato vegetable production, as well as the degree to which the population's demand for vegetables is met, are determined by the development of horticulture in the country.

Tomatoes (*Solanum lycopersicum* L.) hold a significant position among vegetable crops and are one of the most popular worldwide (FAOSTAT, n.d.). Prior to the full-scale invasion, Ukraine had up to 84.3 thousand hectares under tomato cultivation. By 2022, Ukraine ranked 13th globally in tomato production (2.4 million tonnes). However, by 2024, production had decreased to 1.3 million tonnes, placing Ukraine 19th globally. The production of fresh market and processed tomatoes faces numerous challenges caused by diseases stemming from various pathogens. The main groups of pathogens affecting tomatoes include fungi, bacteria, and viruses (FAOSTAT, n.d.). Due to intensive breeding, cultivated tomatoes have reduced genetic diversity, making them more susceptible to over 200 diseases caused by various phytopathogens. This vulnerability has driven researchers to develop new varieties with greater resistance (Panno *et al.*, 2021).

This study aimed to identify and analyse the major diseases affecting tomatoes and to investigate chemical methods for controlling plant diseases and pathogens. To achieve this, the research tasks included analysing the informational basis of the study, as presented in the materials of scientific publications by international authors. These publications, indexed in databases such as Scopus and Web of Science (e.g., *International Journal of Molecular Sciences, Biological Control, Plants, Journal of Plant Biochemistry and Biotechnology, Biocontrol Science and Technology*), provided detailed insights into the chosen topic. The analysis and synthesis of these research enabled a comprehensive understanding of interrelated processes, leading to certain conclusions and the resolution of the research objectives. The abstract-logical method was used to highlight specific features and patterns, facilitating theoretical generalisation based on the obtained data. The object of the study included tomato plants and the pathogenic microorganisms that inhabit them. Over a year, a retrospective analysis of scientific publications on tomato diseases was conducted. No standards, legal acts, or laws were used in the presentation of the material in this article.

PHYTOPATHOGENIC MICROMYCETES AS DISEASE AGENTS IN TOMATO AGROECOSYSTEMS

One of the most well-known and destructive diseases of tomatoes is fusarium wilt, caused by *Fusarium oxysporum*. This disease adversely affects tomato cultivation, causing significant damage at all stages of plant growth. It infects tomato plants and leads to crop losses ranging from 20% to 60, with some cases reporting losses of up to 90%. Additionally, high infection rates in tomato plants have been observed at temperatures around 27°C (Hassan, 2020). For instance, *Fusarium*-induced crop damage in Egypt reached up to 67% (Srinivas *et al.*, 2019).

Fungi of the genus *Fusarium* spp. can also produce secondary metabolites (mycotoxins) in food products, which can lead to contamination in humans and other animals (Alamri *et al.*, 2018; Lombard *et al.*, 2019). In the study of S. Magar *et al.* (2020), it was reported that the application of tebuconazole, and carboxin thiram effectively suppressed mycelium growth, while captan and azoxystrobin showed minimal inhibition, with untreated controls revealing pathogen suppression from ridomil. Agricultural chemicals are commonly used for pest and disease management. Seed treatments with fungicides significantly reduce the incidence of tomato diseases. Key chemicals used to control plant diseases include prochloraz, propiconazole, thiabendazole, carbendazim, benomyl, thiophanate, fuberidazole, and others.

It has been reported that benomyl was partially effective against *F. oxysporum* f. sp. *cubense* using the root-dipping method. This method was also applied with carbendazim on tomato seedlings infected with fusarium wilt, increasing yield by approximately 24% (Hagos *et al.*, 2020). It is worth noting that the overuse of broad-spectrum fungicides adversely impacts the environment and increases the resistance of pathogens to chemical treatments (Kabaş *et al.*, 2020). Another of the most prevalent diseases affecting tomatoes, caused by phytopathogenic fungi, is late blight, caused by *Phytophthora infestans* (Hagos *et al.*, 2020). The detrimental effects of this disease on plants lead to significant agricultural losses worldwide each year. According to N. Jiang *et al.* (2018), in Mongolia, China, and the USA, the late blight pathogen caused substantial tomato production losses in the early 2000s. In the 21st century, the molecular mechanisms of tomato resistance to *P. infestans* remain insufficiently studied, and methods for controlling late blight in tomatoes are still not sufficiently effective.

Infected tomato plants die rapidly. Under high humidity, a light fungal spore coating appears on the plants. Tomatoes become infected with late blight at air humidity levels around 90% (not less than 76%) and at an air temperature of +20°C (Njoroge *et al.*, 2019). Systemic fungicides play a crucial role in combating late blight; however, in cases of disease and favourable environmental conditions, fungicides may not effectively control this destructive issue. Furthermore, the regular use of fungicides contributes to the development of resistance in *P. infestans*. Increased attention is being paid to biological control of crops in the event of disease as an environmentally safe alternative to chemical pesticides. However, biological control agents alone are not sufficiently powerful to combat the threat of devastating late blight under field conditions (Haveri *et al.*, 2018). These factors suggest a need to formulate an integrated system for disease management. Additionally, researchers have explored the potential of using antagonistic bioagents to suppress late blight in tomatoes (Zhi *et al.*, 2021).

In Cameroon, farmers growing tomatoes reported that outbreaks of disease exacerbated the difficulties in maintaining unaffected areas (Vincent *et al.*, 2023). Combating late blight requires aggressive protective measures, which include a combination of host plant resistance and the application of fungicides. Gardeners also utilise various fungicides, such as mancozeb, agrolaxyl, metalaxyl, copper, phosphonic acid, and ridomil (Alamri *et al.*, 2018; Arafa *et al.*, 2022). Among the many available alternative measures, the use of resistant varieties is the most crucial and cost-effective approach to managing the disease (Kassaw *et al.*, 2021). The application of fungicides is a common factor in the early control and management of late blight, both in greenhouse cultivation and field conditions. Additionally, some fungicides exhibit beneficial growth-promoting and physiological effects on plants, leading to a delay in leaf senescence and an increase in chlorophyll content (Arafa *et al.*, 2022). This may contribute to higher yields. Similarly, the results of other field trials indicated that fungicides with systemic or translaminar activity were more effective than protective fungicides (Zafar & Shaukat, 2018).

Another dangerous and damaging disease of tomatoes is early blight, primarily impacting the foliage of the tomato plant. High humidity and temperatures ranging from +24 to +29°C, along with frequent rainfall, create favourable conditions for the growth and spread of *Alternaria solani*. Tomato yield losses can reach up to 80%. To prevent infection by this disease, the use of healthy seeds is essential. Additionally, the pathogen *A. solani* can survive in plant debris and soil through conidia and chlamydospores (Matić *et al.*, 2020). The application of fungicides is crucial for effective control of *Alternaria* leaf spot. Researchers J. Marek *et al.* (2018) noted that many fungicides are registered for combating this disease, particularly those from the chemical groups of strobilurins and carboxamides. Strobilurin fungicides inhibit mitochondrial respiration by blocking electron transport, preventing the proper production of adenosine triphosphate. Similarly, the mode of action of carboxamides involves the inhibition of the enzyme succinate dehydrogenase, thereby reducing the respiratory process by blocking its supply to the fungus.

Among the dangerous diseases affecting tomato agroecosystems is grey mould, caused by the pathogen *Botrytis cinerea*. Under favourable conditions (temperatures up to +20°C and humidity levels of 90%), this ascomycete can cause devastating grey mould infections on tomato plants, leading to yield losses of 20-40% (de Vega *et al.*, 2021). The phytopathogen *Botrytis cinerea* can overwinter in the soil (in the form of sclerotia) and in plant debris. The primary strategy for managing grey mould involves the application of fungicides, including benzimidazoles, quinone inhibitors, phenylpyrroles, and carbamates (Yan *et al.*, 2022). Effective control of *Botrytis cinerea* in agroecosystems is critically important for ensuring stable production. As *Solanum lycopersicum* is a vital crop in the agricultural sector, a successful tomato harvest directly impacts the economic stability of farming enterprises and food security.

PHYTOPATHOGENIC BACTERIA (BACTERIOSES) AS PATHOGENS OF DANGEROUS DISEASES ON TOMATO PLANTS

Bacterioses, like mycoses, pose a serious threat to tomato crops, causing localised epidemics and widespread crop damage (Njoroge *et al.*, 2019; Borzykh *et al.*, 2022). The most common disease is the bacterial canker of tomatoes (caused by *Clavibacter michiganensis*). This pathogen inflicts substantial damage to tomato crops across various countries. At optimal temperatures (+26°C), the pathogen can lead to extensive infections and yield losses of up to 85%. The phytopathogen *C. michiganensis* can survive on seeds and in plant debris.

Disease symptoms usually appear between the fruit setting period and the beginning of ripening, making disease control critical at all stages of plant growth and development. Biological control of pathogenic bacteria involves the use of composting systems, beneficial fungi or bacteria with antagonistic properties against pathogenic bacteria (certain strains of *Bacillus* or *Pseudomonas*). The introduction of beneficial microorganisms (*Trichoderma* spp. or *Bacillus* spp.) into the rhizosphere can suppress the development of pathogenic bacteria through competition or antagonism (Kulimushi *et al.*, 2021). Additionally, the use of phytopathogenic bacteria (*Pseudomonas fluorescens*, *Bacillus subtilis*), which are natural antagonists of pathogens, is promising. However, these biological control methods have shown moderate effectiveness (Zhou *et al.*, 2021). The most recommended methods for detection, prevention, and control of tomato plant pathogens are based on: isothermal amplification, which allows for rapid and sensitive detection of pathogen DNA; end-point visual analysis (detection of specific antigens or antibodies); limiting excess nitrogen fertilisers (optimising fertiliser dosage helps reduce the risk of infection); and seed treatment using high temperatures to reduce the level of infectious load (Haveri *et al.*, 2018; Njoroge *et al.*, 2019). The use of these methods can reduce environmental risks and enable the production of environmentally friendly products.

Another common bacterial disease affecting tomatoes is leaf spot, caused by *Pseudomonas syringae*. The optimal temperature range for the development of this bacterium is between +13 and +28°C, and high humidity further promotes its spread and proliferation (Zhou *et al.*, 2021). Outbreaks of bacterial leaf spots can result in yield losses of up to 75%. The dissemination of this pathogen occurs through infected seeds. The most recommended methods for the detection, prevention, and diagnosis of *Pseudomonas syringae* include polymerase chain reaction and isothermal amplification, which effectively identify the DNA of pathogens (Njoroge *et al.*, 2019). To prevent the spread of *Pseudomonas syringae*, it is essential to use healthy seeds, implement measures to reduce humidity in fields and greenhouses and conduct regular monitoring of plants. According to J. Köhl *et al.* (2020), the application of copper-based bactericides can help reduce the level of infection in tomato plants. Additionally, bacterial strains such as *P. aeruginosa, P. fluorescens*, *P. syringae*, *B. stratosphericus*, and *Azospirillum brasilense* enhance plant growth and improve resistance to viruses.

PHYTOPATHOGENIC VIRUSES IN TOMATO AGROECOSYSTEMS

Viruses exhibit a high potential for rapid adaptation to their environment, including within tomato agroecosystems. This adaptability is facilitated by the high population density and the short generation time for reproduction and spread. When they infect tomato plants, these pathogens lead to decreased yields and reduced quality of cultivated crops (El-Garhy *et al.*, 2020). The most prevalent disease in tomato agroecosystems is the *tomato spotted wilt virus*, which can cause losses of up to 95% depending on the severity of the infection and the developmental stage of the plants. Infection occurs primarily through insect vectors, with mites being the main carriers of the disease (Qi *et al.*, 2021). The optimal temperature range for disease development is between +18 and +27°C and higher.

The most effective methods for controlling and preventing *tomato spotted wilt virus* include selecting tomato varieties that are less susceptible to the virus; controlling vectors through monitoring and management of mite populations; employing agronomic practices; using disease-free seeds and managing plant debris. Integrating these methods creates an effective management system that reduces the risk of virus spread and protects yields. Chemical control of *tomato spotted wilt virus* in tomato cultivation is a crucial aspect of disease management. The primary approaches to chemical control of this virus include the use of fungicides, insecticides, growth regulators, and herbicides. Therefore, controlling *tomato spotted wilt virus* requires a comprehensive approach that encompasses not only chemical means but also agronomic practices that help mitigate the risk of infection and virus spread (Haresabadi *et al.*, 2023).

According to F. Hemmati *et al.* (2023), a significant threat in tomato agroecosystems is the *cucumber mosaic virus*. This virus can adapt to changes in its environment, enabling it to damage various plant species. It is transmitted primarily by insects, particularly aphids, and can result in nearly 100% yield loss in tomatoes (Longe *et al.*, 2022). The *cucumber mosaic virus* can have severe consequences for tomato productivity, including reduced yield; a decrease in both the quantity and quality of fruit; diminished plant vigour and economic losses. Therefore, effective management and control necessitate a comprehensive approach that incorporates both chemical and agronomic methods. The most effective strategies for managing and controlling this virus include the use of chemical and agronomic measures such as insecticides, systemic insecticides, phytosanitary practices, management of agronomic techniques, optimisation of plant care, regular irrigation and fertilisation, sanitation of plants, and the use of resistant varieties. Another dangerous disease posing a serious threat is the *tomato yellow leaf curl virus*. Under favourable conditions for the pathogen, yield losses can reach up to 100%. This plant disease is transmitted by insect vectors and their hosts (Vincent *et al.*, 2023).

Similar to the *cucumber mosaic virus*, the *tomato yellow leaf curl virus* can have severe consequences for tomato yield, including reduced productivity; lower quality and size of fruit; decreased fruit quantity; and economic losses (El-Sappah *et al.*, 2022). Chemical control of the *tomato yellow leaf curl virus* focuses on managing its vectors, as the virus itself cannot be treated with chemical agents. To enhance tomato yield and quality, the following control methods should be employed: phytosanitary measures; vector control (insecticides); crop rotation; and the use of resistant varieties, among others (Kumar *et al.*, 2023). Implementing these methods in conjunction with agronomic practices will aid in more effectively controlling the virus and mitigating its impact on yield.

According to L.E. González *et al.* (2021), the most prevalent virus affecting tomato plants is the *tomato mosaic virus*. This aggressive pathogen causes disease in tomatoes and can inflict significant damage to yields. When cultivated tomato plants are infected, yield losses can range from 30 to 75%. One of the primary pathways for the virus's transmission is infected seeds. Weather and climatic conditions can also influence the manifestation of the disease symptoms. Furthermore, this virus can remain active in infected seeds for up to ten years (Keskse *et al.*, 2019). Research on treating tomato plants has been conducted using zinc oxide. The results demonstrated an enhancement in the plant's immunity against this disease. At 45 to 160 days post-sowing, the plants treated with ZnO nanoparticles exhibited improved growth and photosynthetic properties, increased activity of various antioxidant enzymes, and higher levels of proline and protein compared to untreated plants. The number of fruits and the yield of plants treated with ZnO nanoparticles were also higher (Faizan *et al*., 2020; Arafa *et al*., 2022). In contrast to some other viral diseases, there are no effective chemical agents available for the control or treatment of the *tomato mosaic virus*. Therefore, preventive measures and control of infection are crucial.

An analytical review of the scientific and technical literature allows for the summarisation of the main diseases affecting tomatoes both in Ukraine and globally, as well as the identification of their harmful effects. A systematic analysis of chemical methods for controlling phytopathogens in tomato agrocenoses enables the selection of environmentally safe products, which will reduce pesticide contamination in agroecosystems. This, in turn, will significantly enhance biodiversity levels in agroecosystems, restore balance in the microbiota of agroecosystems, and decrease the cost of plant raw materials. Such measures will reduce the risk of epiphytotics and improve the quality of tomato raw materials. Therefore, the integration of effective disease control and the timely implementation of a comprehensive approach will help mitigate ecological risks, protect yields, and cultivate high-quality, environmentally safe products.

CONCLUSIONS

This review presents a retrospective analysis of the literature, highlighting harmful microorganisms (viruses, bacteria, and fungi) that affect tomato plants and negatively impact the agrocenoses of this crop. Pathogens interact with tomato plants, attacking their vegetative organs, which results in a decline in the quality of plant products, loss of yield, and partial or complete plant death. The influence of pathogens on tomatoes has been analysed, along with the degree of pest intensification in the plants, as well as methods for combating these pathogens. The functioning of fungicides from various chemical groups and origins against phytopathogens is also discussed, as they are a critical factor in preventing the spread of diseases affecting tomato plants. The main diseases are caused by fungi of the genera *Alternaria, Fusarium*, *Phytophthora*, and *Botrytis*. Additionally, viruses (such as the *tomato spotted wilt virus* and the *tomato yellow leaf curl virus*) and bacteria (including bacterial canker of tomatoes and bacterial spot) are also covered.

Chemical control in agriculture plays a crucial role in addressing the challenges posed by pathogens affecting tomatoes. It is essential to utilise appropriate chemical agents, taking into account the type and stage of the disease. This approach will facilitate the effective management of tomato plant diseases and enhance their yield. Understanding the primary diseases that can afflict tomatoes enables the timely identification of disease symptoms and the prompt implementation of preventative and therapeutic measures. Effective plant protection substances against pathogens include chemicals such as thiabendazole, prochloraz, benomyl, propiconazole, thiofanate, and fuberidazole. For the control of plants infected with *Phytophthora*, effective fungicides include agrolyxil, mancozeb, ridomil, copper, and phosphonic acid. In the fight against *Alternaria*, carbamate and strobilurin fungicides are recommended, while for grey mould, the use of benzimidazole, phenylpyrroles, and quinone inhibitors is effective. The information gathered has allowed for an analysis of tomato diseases and their pathogens, as well as a review of the chemical agents used and their impact on these diseases. This knowledge will enable agricultural producers to promptly identify issues and take necessary actions to cultivate high-quality yields with minimal damage and loss.

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CONFLICT OF INTEREST

None.

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Огляд основних хвороб *Solanum lycopersicum* та методи хімічного контролю патогенів

Лілія Гаврилюк
Доктор філософії, старший дослідник
Інститут агроекології і природокористування Національної академії наук України
03143, вул. Метрологічна, 12, м. Київ, Україна
https://orcid.org/0000-0001-6901-0766

Ірина Безноско
Кандидат біологічних наук, старший дослідник
Інститут агроекології і природокористування Національної академії наук України
03143, вул. Метрологічна, 12, м. Київ, Україна
https://orcid.org/0000-0002-2217-5165

Данило Гуменний
Аспірант
Інститут агроекології і природокористування Національної академії наук України
03143, вул. Метрологічна, 12, м. Київ, Україна
https://orcid.org/0009-0009-2936-4506

Дмитро Гентош
Кандидат сільськогосподарських наук
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 13, м. Київ, Україна
https://orcid.org/0000-0001-8647-7843

Олена Башта
Кандидат біологічних наук
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 13, м. Київ, Україна
https://orcid.org/0000-0003-4682-1595

Анотація. У статті наведено перелік основних хвороб рослин томатів (*Solanum lycopersicum*), що спричиняються вірусними, бактеріальними та фітопатогенними мікроорганізмами. Патогенні мікроорганізми, паразитуючи на рослинах томатів, викликають великі втрати врожаю в сільськогосподарському виробництві, знижуючи якість продукції. Метою дослідження було з'ясувати вплив мікроорганізмів на рослини томатів, ступінь їх шкодочинності та методи боротьби зі збудниками хвороб. Встановлено, що основні хвороби рослини томатів викликані грибами роду: *Fusarium* (фузаріоз), *Phytophthora* (фітофтороз), *Botrytis* (сіра гниль), *Alternaria* (альтернаріоз); віруси *Omato spotted wilt virus* (вірус плямистого в'янення), *Tomato yellow leaf curl virus* (вірус жовтого скручування листя), бактерії *Ascochyta cucumis* (бактеріальний рак томатів), *Xanthomonas vesicatoria* (бактеріальна плямистість). Проаналізовано, що сільськогосподарські хімікати є важливою складовою для управління шкідниками та хворобами, тому основним засобом боротьби з хворобами рослин є хімічні речовини, такі як прохлораз, тіабендазол, пропіконазол, карбендазим, беноміл, тіофант, фуберідазол та ін. Досліджено, що системні фунгіциди відіграють важливу роль у боротьбі з різними хворобами, виявляють корисну фізіологічну або стимулюючу ріст дію на рослини, включаючи затримку старіння листя, підвищення вмісту хлорофілу. Встановлено, що у боротьбі з альтернаріозом ефективним є застосування фунгіцидів (хімічна група стробілурін і карбоксамід), а основною стратегією боротьби з сірою гниллю є хімічний контроль шляхом застосування синтетичних фунгіцидів: інгібітори хінону, бензімідазолу, карбамати, фенілпіроли та інгібітори сукцинатдегідрогенази. Огляд хвороб та методів хімічного контролю патогенів є надзвичайно корисним для застосування у сільському господарстві. Практична цінність дослідження полягає в тому, що ця інформація допомагає сільськогосподарським виробникам ефективно управляти врожаєм та зберігати якість плодів. Знання про основні хвороби, які можуть уражувати томати, дозволяє вчасно виявляти симптоми та вживати відповідні заходи для їх запобігання та лікування

Ключові слова: мікроскопічні гриби; томати; хімічні речовини; бактерії; віруси; агроценоз