SPECIFICS OF PRESENTATION FOR PHYSIOLOGICAL DISORDERS IN TOMATOES

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Abstract. *Disorders and difficulties in plant growth and development can also arise from factors other than those caused by infectious contamination. Tomatoes, like other agricultural crops, are often exposed to inappropriate environmental conditions. During the growth period, extreme temperatures, heat stress, insufficient or excessive light, frost, soil moisture deficit, nutrient deficiencies or excesses, as well as some effects resulting from inappropriate application of plant protection products frequently affect plants. Although tomatoes tolerate a relatively wide range of climatic conditions - allowing cultivation in diverse production environments - obtaining high yields requires specific growth and development conditions considered optimal. Whether grown on an industrial scale, on small plots or in home gardens, tomato cultivation requires systematic monitoring of plant health. Understanding the conditions that trigger physiological disorders and ways to strengthen plant health are of particular importance for increasing resistance to potential attacks by infectious diseases and pests. Knowledge of the symptoms of physiological disorders under different production conditions contributes to obtaining high yields and quality products.*

Keywords: Physiological disorders, tomato symptoms, environmental conditions.

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1. Introduction

Tomatoes are widely cultivated in open fields, polytunnels, greenhouses, and other types of protected environments, using natural soil, sand, or artificial growing substrates. Increasing consumer demands, combined with environmental concerns and a shift toward organic production, have led to significant changes in tomato cultivation technologies. The focus has shifted toward sustainable production, which aims to achieve a competitive, high-quality harvest while reducing the use of polluting inputs. In this context, it should be noted that tomato crops are susceptible to various diseases and pests, which, under conditions favorable to their development, can cause irreparable damage. The ability to prevent the emergence and spread of infections, or to mitigate the impact of such outbreaks, becomes the primary factor determining success in this type of endeavor. Furthermore, the

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potential effects of climate change, such as an extended growing season, lower temperatures in the spring, temperatures exceeding the optimum in the autumn and winter, or irregular precipitation patterns—cannot be ignored, as these factors can influence the onset and progression of certain diseases [3, 27].

Physiological disorders and plant growth difficulties can also be caused by factors other than infectious pathogens. Throughout the growing season, plants are frequently affected by extreme temperatures, insufficient or excessive light, frost, and soil moisture deficits [9]. Industrial development, the growing number of means of transport, and other social and economic factors characterized by high energy consumption have led to an increase in the volume of gases emitted into the atmosphere, as well as in the amount of harmful compounds released into water and soil [37]. Instances where plants suffer damage, whether due to acid precipitation [16], the use of contaminated water for irrigation, or the improper application of treatments against diseases and pests, are becoming increasingly frequent.

Conducting a comprehensive analysis of the effects of climate change on the emergence of diseases and the control of their progression is becoming increasingly difficult. This is because, in addition to the phenotypic diversification resulting from the use of new genetic technologies in plant breeding, the instability of abiotic factors triggers various physiological disorders, manifesting as symptoms that resemble those caused by certain pathogens [8]. There is already clear evidence that global warming and climate change [9] will influence the occurrence and severity of harmful agents affecting plants. This will impact disease management, particularly regarding the timing of agrotechnical operations, the application and efficacy of chemical, physical, and biological control measures, and how these are integrated into plant protection strategies. The complexity of the risks involved in managing phytosanitary status can be significantly reduced if one also considers the symptoms characteristic of physiological disorders, disorders that arise when growing conditions do not align with the requirements of the plants' ontogeny.

Whether tomatoes are grown on an industrial scale, on smaller plots, or in home gardens, a systematic assessment of the plants' condition is essential. Although symptoms caused by bacterial, fungal, and viral diseases are extensively documented in the specialized literature [11, 13], they are frequently associated with, and can easily be confused with, morphological changes and various disturbances in growth and development resulting from growing conditions that deviate from the optimum. There are numerous situations in which plants exhibit etiolation, yellowing, the wilting of certain parts or organs, or various types of spots or lesions, symptoms that, at first glance, resemble those caused by infections [15, 22, 27]. The inability to manage and maintain technical parameters in accordance with optimal requirements, based on a diagnosis of the plants' physiological state, can lead to the excessive use of plant protection products, resulting in

environmental pollution and the contamination of agricultural produce with harmful substances

Climate change alters the epidemiology of diseases and necessitates the development of adaptive strategies for integrated disease management [21]. Under current circumstances, preventive measures are of particular importance, being considered the most appropriate and relevant approach in plant protection. In this context, recognizing symptoms, understanding the conditions that trigger physiological disorders, and knowing how to strengthen plant health are crucial for increasing resistance to potential attacks by various pathogens and pests; this, in turn, contributes to achieving high yields and quality produce.

2. Materials and methods

Phenological data were collected through multifactorial experiments conducted under various pedoclimatic conditions at the following institutions: the Institute of Genetics, Physiology and Plant Protection; the Scientific-Practical Institute of Horticulture and Food Technologies (Chisinau); the "Porumbeni" Institute of Crop Science (Pașcani); and the Institute of Vegetable Growing and Irrigation Technologies (Tiraspol).

Over the years, specific experimental phases were evaluated to analyze and determine the responses of various tomato genotypes exposed, throughout the entire growing season, to thermal and water stress, as well as to a wide range of nutritional levels. This evaluation included the characterization of morphological traits, documented through photographs taken under diverse plant cultivation conditions.

Throughout the growing season, phenological observations were conducted regarding plant growth and development, as well as morphological changes and variations in the coloration of vegetative organs and fruits during the ripening stage. The underlying causes of physiological disorders and reduced plant resistance to abiotic stressors were analyzed visually and examined based on symptoms described in the specialized literature.

The assessment of physiological disorders in plants involves the use of a set of visual and biochemical techniques designed to identify deviations from normal metabolism. In this context, visual diagnosis is the most accessible method [22], as it relies on the correlation between external symptoms and internal biochemical disturbances within the plant. Changes in leaf color, such as yellowing (chlorosis) along the margins or in the areas between the veins, often indicate a deficiency in nitrogen, magnesium, or iron [15]. Reddish or purplish hues may signal a phosphorus deficiency or thermal stress caused by unsuitable temperatures. Malformations and necrosis, manifesting as leaf curling or crinkling, thinning of leaf tips, or the appearance of dry spots (in the absence of spores or parasites), point to hydrothermal shock or chemical burns [27].

3. Results and Discussions

3.1. Physiological disorders caused by imbalances in environmental factors

Environmental factors are of particular importance for the growth and development of tomato plants; among these, temperature, light, water availability, and nutrient supply play a primary role [3, 10]. Like other agricultural crops, tomatoes are constantly exposed to fluctuations in environmental factors. Throughout the growing season, plants are frequently affected by extreme temperatures, frost, soil moisture deficits, as well as nutrient deficiencies or excesses.

To achieve higher yields, plants require specific conditions for growth and development, conditions considered relatively optimal. Although tomato plants can tolerate significant fluctuations in climatic factors with relative ease [4, 12], a trait that allows them to be cultivated across a variety of geographical regions and production environments, it should be noted that extreme temperatures, water deficits (in both the soil and the atmosphere), excessive or insufficient solar radiation, intense heat, drought, and frost all represent risk factors. These elements limit the productivity, stability, and quality of tomato harvests.

In general, minor, short-term fluctuations in climatic factors do not cause significant disruptions to the physiological functions of the plants. The term "moderately unfavorable conditions" refers to factors whose intensity and duration, while not immediately lethal, trigger a wide range of long-term consequences for physiological processes, ultimately having a negative impact on final productivity [35, 36].

The temperature of the soil or growing medium directly influences germination, root growth, and the functionality of the root system. Seed germination occurs at temperatures above 10–12 °C, but below 35 °C. The development of the root system is largely determined by the temperature of the growing medium [28, 29]. Temperatures below 5–6 °C cause root function to cease, while at values below 0 °C, the roots die. Root growth and development are also inhibited at temperatures exceeding 30–35 °C. Extreme temperatures in the root zone affect other plant organs, as well as the plant as a whole.

At temperatures below 5 °C, water in the soil becomes unavailable; however, plants regain their absorption capacity as the temperature rises above 12–15 °C, although this capacity decreases again at temperatures above 25 °C [4].

Nutrient uptake occurs within temperature ranges similar to those required for water absorption. The ammoniacal form of nitrogen (NH_4^+) is absorbed more readily at relatively low temperatures (8–14 °C), whereas the nitrate form (NO_3^-) is assimilated more easily as the temperature increases (24–34 °C) [1]. Phosphorus (in the form of P_2O_5) is assimilated more readily at temperatures above 20 °C. Air temperatures below 10 °C can negatively affect plant growth, leading to a negative bioconversion balance [12]. At higher temperatures, synthesized substances are primarily directed

from the leaves toward the fruits, at the expense of root growth, whereas at lower temperatures, they are directed more toward the roots than the fruits. Consequently, at temperatures below 18 °C, tomato plants yield smaller harvests compared to optimal levels [10].

During the ripening period, fruit color is largely determined by temperature. Low temperatures inhibit the synthesis of lycopene, which dictates the intensity of the red color—while temperatures above 30 °C significantly reduce the formation of this pigment. Under such conditions, the synthesis of beta-carotene predominates, giving the fruits an orange hue. The inhibition of lycopene synthesis at temperatures above 30 °C (and of carotene at temperatures exceeding 40 °C) results in uneven ripening, characterized by the appearance of yellow or yellow-green patches against the red background of the fruit [18]. High temperatures also inhibit the synthesis of enzymes responsible for tissue softening; at the stage of biological maturity, this often leads to fruits with a firmer, harder consistency, which significantly diminishes their eating quality. In field conditions, tomato plants can be negatively affected by large temperature fluctuations, as well as by spring and autumn frosts. For vigorous growth, tomato plants require daytime temperatures between 19 and 24 ºC and nighttime temperatures of 16–18 ºC. Air temperatures below 10 ºC inhibit vegetative growth and development, reduce fruit set, and impair ripening; conversely, temperatures exceeding 35 ºC decrease the number of fruits and diminish their color intensity.

Well-hardened seedlings, once planted in the soil, can withstand short-term exposure to temperatures as low as –1.5 to –2 ºC; however, such conditions severely affect the plants, reducing their productivity by 30–50% and delaying the onset of fruiting by 8–10 days. It is a well-known fact that young plants are more sensitive to low temperatures than mature ones. Even light frosts or prolonged periods of low temperatures can cause flower drop and lead to the appearance of translucent or waxy-looking spots on leaves and young fruits, which subsequently rot.

The destruction of tomato seedlings can also occur in protected environments. Damage to seedlings due to frost—especially after planting in unheated greenhouses, is a critical issue, often resulting in irreversible damage. In unheated greenhouses covered with polyethylene film, when the ambient air temperature drops to –4 ºC, the temperature at the plant surface can fall to –1.5 ºC, while the temperature in the spaces between the plants reaches 0.5–1 ºC.[6] At such temperatures, 30–40% of the seedlings perish (Fig. 1).

If the growing point and the first inflorescences are damaged, tomato plants may sometimes develop lateral shoots that continue vegetative growth; however, in such cases, the efficiency of an early crop is significantly reduced. At temperatures of –3 ºC, tomato plants suffer severe damage—though they may occasionally recover, but such crops require additional effort and expense for restoration, rendering the recovery and maintenance process unprofitable. Initial symptoms of frost damage in

tomato plants appear within a few hours, but a definitive assessment of the extent of the damage and the resulting losses can only be made after 2–3 days.



a. before planting **b**. after planting

Fig. 1. Damage to plants due to frost

Tomato plants grown from early direct sowing in open fields are relatively more resistant to frost compared to crops established via transplants. In field conditions, seedlings at the stage of having one true leaf can withstand short-duration frosts down to –4 ºC [6]. Ripe fruits are particularly sensitive to frost; they lose their flavor and processing quality at temperatures of –0.4 to –0.5 ºC.

Light plays a crucial role in the growth and development of tomato plants, largely determining their flowering capacity, fruit set, fruit formation, and fruit quality. While its influence is not as profound as that of temperature, insufficient light during the seedling stage can lead to the total failure of the crop, as the excessive elongation of seedlings significantly increases risk. A lack of light during this phase also affects the development of reproductive organs [18, 36].

Low light levels can significantly impair plant growth and development, especially in protected cultivation environments during winter and spring. Under conditions of low solar radiation, fruits from the first inflorescences may develop internal cavities, exhibit a lower dry matter content, and possess a thinner skin that is prone to cracking upon maturity (Fig. 2).

Light intensity and quality are of particular importance regarding the accumulation and redistribution of substances assimilated during the photosynthesis process. When plants are grown under low-light conditions, the quantity of photosynthetic products in the leaves is lower; consequently, these products are redirected toward increasing the assimilation surface area—which has a low photosynthetic yield—at the expense of flower initiation, fruit set, and fruit development [24]. This explains why flowers may abort when exposed to insufficient light intensity over an extended period.



Fig. 2. Symptoms characteristic of light deficiency in the context of low temperatures

In greenhouse conditions, insufficient light leads to irregularities in fruit development; the fruit skin becomes thinner and prone to cracking when environmental parameters fluctuate. Fruit cracking occurs most frequently at the beginning of the ripening stage. In some cases, fruit cracking is caused by high nitrogen levels in the soil. Under conditions of chronic light deficiency in enclosed spaces, the negative impact on photosynthetic processes can be partially mitigated by enriching the atmosphere with carbon dioxide [18]. Unlike temperature, light has a less significant influence on fruit ripening, yet it directly affects the content of dry matter, carotene, and other biochemical compounds (Fig. 3).



Fig. 3. Cracked fruits caused by insufficient light.

A prolonged lack of light during the fruit development phase leads to the formation of a much thinner skin, which tends to crack easily on very sunny days, a factor that negatively affects fruit quality. In such cases, fruits located at the

base of the cluster, as well as those that developed during periods characterized by frequent cloud cover and low light levels, are the most severely affected.
Sunscald occurs primarily in determinate (bush-type) tomato plants with small leaves. On green fruits, whitish spots appear; these areas dehydrate and eventually become sunken. On ripe fruits, yellow spots appear. The affected areas lose turgor, wilt, and can lead to tissue rot on the fruit's surface (Fig. 4). To mitigate sunscald damage in tomatoes, it is essential to ensure conditions that promote vigorous vegetative growth in open-field cultivation and to use shade netting in greenhouses during the summer. Thanks to advances in plant breeding, varieties and hybrids have been developed that are adapted to the climatic conditions of various geographic regions, as well as to different cultivation systems, such as greenhouses, polytunnels, or open-field production. Currently, there are genotypes specifically developed for greenhouse cultivation during the winter, which require light intensities of 8,000–12,000 lux, as well as genotypes intended for open-field cultivation, which require 14,000–25,000 lux to achieve higher yields.



Fig. 4. Sunscald on green and ripe fruits

Water, as a factor in plant growth and development, plays a primary role in achieving higher tomato yields. Requirements for atmospheric humidity are relatively moderate, while those for soil moisture are significantly higher. Although tomato plants can, to some extent, tolerate short-term atmospheric or soil drought, such conditions negatively impact productivity—particularly if the moisture deficit occurs during the fruit-setting and development stages. This effect is less significant when the plant already bears a sufficient number of fruits that are in the ripening phase. These observations indicate that tomato plants have varying water requirements depending on their developmental stage [2].
Research conducted over several years at the Institute for Plant Breeding and Vegetable Growing in Tiraspol suggests maintaining a minimum soil moisture

level of 70% of field capacity up until the flowering stage, increasing to 80% during the fruit formation and ripening periods [34].

The optimal soil moisture level depends largely on plant density, soil porosity, and the degree of root system development. Plants grown from direct field sowing are more resilient regarding water availability because they develop taproots that penetrate deeper and extract water from a larger volume of soil; in contrast, plants raised from transplants develop fibrous root systems concentrated primarily in the upper soil layers. Fluctuations in root-zone water content, ranging from maximum to minimum levels and vice versa, are particularly hazardous, as they induce water stress, leading to various physiological disorders and negatively impacting both yield and produce quality. If seed germination is triggered but followed by low soil moisture, the germinating seeds or seedlings may die during the early stages of development.During the seedling growth stage, excess moisture, combined with high temperatures and/or low light intensity, leads to plant elongation. If soil moisture is low, the plants wilt. In some cases, this physiological state is reversible, allowing the plants to gradually recover; in more severe instances, the plants die.



Fig. 5. Non-infectious leaf curling.

Due to their well-developed root systems, mature plants are less susceptible to water stress. However, significant fluctuations between low and high moisture levels, particularly in protected cultivation environments, often result in the formation of cracks at the base of the stem, which facilitate the entry of pathogens.

Initially, water stress does not produce clearly visible symptoms on the leaves. Nevertheless, under conditions of acute and prolonged drought, the plant's metabolism, the redistribution of assimilates, and the structure of its tissues and organs are all affected. In the absence of sufficient moisture, leaves wilt; in certain

genotypes, they also curl around the veins. In some varieties, leaf curling is a genetically determined trait that enhances the plant's adaptation to atmospheric and/or soil drought (Fig. 5).

Inadequate water supply over an extended period leads to pollen grain infertility, as well as the shedding or abortion of flowers. At the same time, excessive air humidity creates unfavorable conditions for the opening of anthers and the release of pollen. In some cases, fruit cracking is caused by sudden changes in the moisture level of the soil or growing medium [19]. During periods of high temperatures and sunny weather, the soil can overheat and dry out. If heavy irrigation is applied under these conditions, large quantities of water are transported to the fruits; their walls cannot withstand the resulting osmotic pressure and consequently crack (Fig. 6). To prevent fruit cracking, it is necessary to maintain optimal soil moisture and an appropriate plant nutrition regimen



Fig. 6. Fruit cracking caused by a sudden change in soil moisture



Fig. 7. Fruits with reduced quality due to physiological disorders caused by environmental factors

Excess moisture during fruit ripening, following a relatively dry period, leads to fruit cracking and quality degradation, even under open-field conditions (Fig. 7). Some recommendations suggest reducing soil moisture levels during the biological ripening stage and harvesting the fruit at the "waxy" phase or at the onset of the transition to red. It is well established that fruit ripened under conditions of limited water supply possess superior flavor, owing to a higher dry-matter content and a more balanced ratio of sugars to acids.

Air. Intense air circulation combined with high temperatures and low humidity causes excessive flower drop (Fig. 8). Relative air humidity is considered optimal when it ranges between 55–60% during the first vegetative stage and 65–70% during the second. Excess air humidity promotes the development and spread of diseases affecting foliage and fruit. To prevent sudden fluctuations in air humidity, airflow within the greenhouse should be maintained at a rate of 1–1.5 m/s.



Fig. 8. Absence of flowers and young fruits caused by low air humidity

Carbon dioxide is a component of the air (0.03%) of particular importance, as it enables the process of photosynthesis. CO_2 levels are actively managed when cultivating tomatoes in protected environments [18]. It has been observed that increasing the CO_2 concentration to 0.09–0.14% enhances photosynthesis, resulting in more vigorous plant growth and development. During the day in the winter season, it is recommended to maintain the CO_2 concentration in the greenhouse air at 800–1,000 ppm. Excessively high carbon dioxide levels can lead to negative effects, impacting both the plants and pathogenic organisms.

The relationship between plants and the air becomes increasingly significant when the air's composition undergoes substantial changes due to uncontrolled gas emissions and excessive pollution. Following a prolonged period of atmospheric drought, light precipitation can trigger the appearance of various spots or rust-like lesions on leaves, stems, and fruits, not only in tomatoes but also in other plant species, which are frequently mistaken for symptoms of infectious diseases.
The role of oxygen in biological processes is well-recognized and documented from various perspectives. Tomato plants are sensitive to root asphyxiation caused by low oxygen wqlevels in the soil. A reduction in oxygen content within the root zone, often occurring in compacted or waterlogged soils, impairs the function of active roots, leading to premature aging and even root death. When oxygen is insufficient, the recovery of the root system is a lengthy process.

3.2. Soil Requirements

Tomatoes yield higher harvests when grown in chernozem, sandy-clay, or clay-sandy soils that are rich in humus, well-structured, and well-managed, provided the groundwater table is at a depth of more than 4 meters. Satisfactory results can also be achieved in well-drained heavy soils. Light soils have a lower water-retention capacity, which exacerbates moisture deficits, leading to water stress during periods of drought or insufficient irrigation. Heavy soils warm up more slowly and, if compacted or excessively wet, can cause root system asphyxiation.
Tomatoes are sensitive to root asphyxiation resulting from soil compaction and an excess of water that reduces soil porosity. Prolonged asphyxiation can trigger symptoms of various nutrient deficiencies, such as those of phosphorus, magnesium, or nitrogen, which increase the plants' vulnerability to infectious diseases.
For tomato cultivation, the soil must be well-supplied with organic matter and essential nutrients, and it should have a pH between 6 and 7. The pH level specifically influences nitrogen uptake [1], depending on whether the nitrogen is in nitrate (NO_3) or ammonium (NH_4) form. If the pH drops below 5 or rises above 7, there is a significant reduction in stem growth and overall plant habit (Fig. 9). Higher pH values in the soil or substrate inhibit the uptake of phosphorus, boron, copper, iron, magnesium, and zinc, whereas lower pH values reduce the availability of molybdenum [31].



Fig. 9. Disorders caused by high acidity of the nutrient substrate

Tomatoes exhibit moderate tolerance to soil salinity (2.5 dS m^{-1}); however, it is preferable for soils to have salinity levels within a normal range, specifically, they should be free of chlorides and sodium [25, 28]. The adverse effects of excessive salinity are most likely to occur when crops are established on land with a high water table, or when irrigation water containing salt concentrations exceeding 1 g/l is used extensively over a prolonged period.

3.3. Physiological disorders caused by nutritional status

Plant nutrition is a complex physiological process consisting of the uptake, primarily by the roots, and to a lesser extent by the leaves, of accessible mineral substances from the root zone. These substances are then transported and metabolized into organic compounds essential for growth. Subsequently, they are incorporated into various structural components, most notably carbohydrates and proteins, which, through degradation, provide the energy required for vital life processes.

Along with water and other environmental factors, nutrients are frequently in short supply relative to the plant's requirements. Consequently, ensuring an optimal supply of nutrients, balanced according to the specific needs of the plant, is a prerequisite for achieving high yields and superior quality. A deficiency or an excess of nutrients triggers various physiological disorders [32], which negatively impact plant vigor, resistance, productivity, and the quality of the produce.

Under conditions of water scarcity, root growth is impaired, resulting in a weaker root system; in such cases, the uptake of nutrients becomes more difficult. Extreme temperatures also disrupt plant metabolism, which can lead to the emergence of various nutrient deficiencies and physiological disorders.

Assessing the nutritional status of plants based on visible symptoms is a primary, yet subjective, method of evaluation. This assessment is based on identifying states of nutrient deficiency or toxicity, manifested through symptoms appearing

on various plant organs. These symptoms are specific to each element and its particular mode of expression, while also being influenced by the biological characteristics of the varieties and the conditions under which the crop is maintained. Through this approach, one can evaluate several aspects, including: the general condition of the plants at different stages of growth and development; the ratio between the root system and the aerial parts; the growth rate; stem length and leaf orientation; the positioning of inflorescences along the stem; the number of flowers and fruits per cluster; fruit size and internode length; and leaf coloration, using a standard green hue as a reference for a healthy nutritional status, among other factors.

In some instances, an excess or deficiency of multiple nutrients relative to the plant's requirements may result in complex, interrelated symptoms [14,15], sometimes exacerbated by unfavorable environmental or production conditions. In such cases, determining the plant's nutritional status is best achieved through chemical analysis of plant tissues and the soil, an effective method for assessing the level of nutrient supply.

Managed plant nutrition entails ensuring optimal conditions for growth and development. Occasionally, symptoms of physiological disorders stemming from nutritional imbalances can be mistaken for signs of pathogen-induced infections, potentially leading to the application of treatments based on an incorrect diagnosis. Accurately diagnosing nutritional imbalances and specific nutritional requirements is of great importance for optimizing plant growth and development. When applying supplementary fertilizers, this can help mitigate the impact of disturbances caused by environmental factors (light, temperature, humidity, air composition), while simultaneously strengthening the plants' resistance to various diseases.

Nitrogen is the most important nutrient for plant life, playing a decisive role in increasing tomato yields. A plant's nitrogen requirement varies throughout its growth cycle. In the early stages of development, plants have relatively low nitrogen demands within the root zone; the greatest amounts are assimilated during the period of intensive vegetative growth and fruit formation.

Due to its high mobility and capacity for translocation within the plant, symptoms of nitrogen deficiency first appear on mature leaves at the base of the stem or shoots, subsequently spreading toward the upper leaves. Insufficient nitrogen supply in the soil, or poor nitrogen uptake, visibly reduces plant vigor. In such cases, the leaves take on a lighter color (Fig. 10), and the fruits become smaller and of inferior quality. Easily observable symptoms, which generally indicate a deficiency of this nutrient, include a loss of green color intensity, etiolation, short stems with thin tips, small leaves, and sparse or delayed flowering. Nitrogen deficiency leads to reduced vegetative growth rates and a shortened growth cycle,

both of which negatively impact productivity. The fruits exhibit inferior flavor, reduced flesh firmness, and poor resistance to transport and storage [1].



Fig. 10. Symptoms characteristic of nitrogen deficiency

In cases of severe deficiency, the main stems are shorter and have few branches; the leaves turn yellow and then brown, starting at the tips and margins—before wilting and drying out. This yellowing may be followed by premature defoliation [15]. In some varieties, the main veins and petioles of the lower leaves take on a red or anthocyanin-like coloration. An excess of nitrogen during the seedling growth stage causes the plants to elongate, a response similar to that triggered by a lack of light, or an excess of water or heat, which makes it difficult to diagnose. Under such conditions, it becomes more challenging to properly "harden off" the seedlings before transplanting.

Excessive nitrogen fertilization during the growing season has negative effects: it promotes vigorous stem and leaf growth at the expense of fruit production and early maturity, while also reducing the plants' resistance to extreme environmental conditions and pathogens. Symptoms appear on mature leaves at the base of the stem; as temperatures rise, these leaves may resemble those damaged by frost or "scalded," showing burns at the tips and margins.

In mature plants, a moderate excess of nitrogen can be identified by thick, rigid stems, lush foliage with an intense green color, and leaves that appear curled or puckered, often accompanied by a lack of inflorescences. Tomato plants are particularly sensitive to an excess of ammoniacal nitrogen, which inhibits calcium uptake. Ammonium toxicity leads to the yellowing of the leaves.

Phosphorus. This element plays a primary role in plant metabolism, being involved in the most important physiological processes. Phosphorus participates in a range of processes related to the formation of organic compounds, such as nucleic acids and phospholipids, contributes to the development and quality of fruit, stimulates root system growth, and enhances plant resistance to adverse conditions, including extreme temperatures, moisture deficits, diseases, and pests.

Phosphorus has low mobility in the soil, combined with a very high retention capacity. The total content of this element remains relatively stable [31]. Most soils have the capacity to retain phosphorus, with the exception of sandy soils. To prevent phosphorus deficiency in plants, it is essential to ensure the availability of this element, in forms that are easily accessible to the plant, starting from the earliest stages of growth.

A deficiency of phosphorus in the soil or nutrient substrate leads to various physiological disturbances (Fig. 11) and a slowdown in plant growth rates. When plants are under-supplied with phosphorus, the mobility of this nutrient ion within the plant triggers a redistribution of phosphorus from mature organs to younger ones. Consequently, signs of deficiency first appear on older leaves, which remain small and rigid, and develop a purplish hue on their undersides. In cases of more severe phosphorus deficiency, fruit cracking may occur.



Fig. 11. Symptoms characteristic of Pdeficiency Phosphorus deficiency associated with an excess of Cu, Mg, or Zn

An excess of phosphorus leads to the accumulation of its mineral form within plant organs. Plants exhibit slowed growth and premature aging, which results in lower yields. Furthermore, an excess of phosphorus can affect the availability of other elements, such as zinc and copper, and can disrupt the uptake of these nutrients by the plant.

Potassium plays a particularly important role in plant nutrition and is absorbed by plants in large quantities compared to other nutrients, with the exception of nitrogen. In some cases, the total potassium content in chernozem soils exceeds the amount required to sustain plants throughout their entire growing season; however, it should be noted that only a small fraction of the soil's potassium is actually available for plant nutrition. Nevertheless, to achieve higher yields and better quality, tomatoes require additional potassium fertilization, even in soils already rich in this element.

Available potassium (K_2O) is the form most accessible to plants, as it is absorbed by the roots from the soil solution. The rate of potassium uptake depends on several factors: the type of crop (direct-seeded, transplanted, or grown in a greenhouse on various substrates, etc.), the development of the root system, the stage of the growing season, the level of potassium present in the active root zone, and the presence of other cations that may inhibit the uptake of this element.

As an essential element for plant metabolism, potassium, when assimilated in sufficient quantities, enhances drought resistance, stimulates chlorophyll synthesis, and boosts the rate of photosynthesis [26]. Potassium deficiency in tomatoes significantly reduces both plant productivity and fruit quality. Inadequate supply of accessible potassium impairs the enzymatic processes responsible for converting sugars into starch, which leads to the accumulation of sugars in the fruit and a decline in overall quality. Potassium is involved in regulating the water balance within a plant; a deficiency causes stomata to remain locked in an open position. Consequently, potassium helps reduce water loss through transpiration and enhances plant resistance to water stress and extreme temperatures.

When this element is deficient, tomato plants exhibit symptoms resulting from metabolic disruption, which leads to premature aging and reduced resistance to various infections, as well as to adverse temperature and humidity conditions. Potassium deficiency manifests primarily on mature leaves, as the element is translocated, much like nitrogen, from mature tissues to younger ones. The deficiency appears as yellow-brown spots, starting at the leaf margins and spreading inward across the leaf blade; these eventually take on the appearance of burns (Fig. 12).



Fig. 12. Symptoms characteristic of potassium deficiency

Under conditions of potassium deficiency, fruits ripen unevenly, develop irregular shapes, are prone to the formation of internal cavities, and exhibit inferior taste quality. Such symptoms may occur when tomatoes are grown in clay or sandy soils, or when using growing media that are inadequately supplied with potassium. In certain situations, sodium can substitute for potassium and perform some of its secondary functions; however, this process negatively affects the taste quality of the fruits.

Excessive potassium fertilization can lead to toxicity, manifesting as leaf necrosis and stunted plant growth. This occurs because the uptake of nutrients, such as nitrogen, phosphorus, magnesium, and zinc, is blocked, leading to various physiological disorders.

Calcium is essential for plants and plays a direct role in physiological processes, serving primarily as a structural component in the formation of pectocellulosic membranes [5]. Calcium supports the development of the root system, strengthens the supporting tissues within the stem, promotes vigorous plant growth, and enhances resistance to breakage as well as to stressors caused by unfavorable growing conditions. Plants assimilate calcium through their root system by absorbing the relevant ions from the soil solution. A calcium deficiency in the soil, or limited availability due to an excess of another element, such as potassium, can lead to various physiological disorders that reduce both the yield and the quality of the fruit.

Calcium, sulfur, and magnesium, classified as secondary macronutrients, play a significant role, as plants require them in relatively large quantities. Since these elements are generally present in the soil in substantial amounts, it is often assumed that the plants' requirements are largely met; consequently, they are not typically applied as standalone fertilizers, unlike nitrogen, phosphorus, or potassium. However, in tomato cultivation, particularly when artificial substrates are used, situations frequently arise where it becomes necessary to supplement the levels of these elements through the application of specialized fertilizers.

In intensively irrigated fields and protected cultivation environments (greenhouses and polytunnels), calcium is easily lost through leaching. A deficiency manifests as stunted growth and curled, light-green leaves, while the growing tip (apical meristem) may dry out. Foliar application of calcium helps plants recover from stressful conditions, fostering greater stress tolerance while also enhancing the nutritional value and quality of the produce [30]. Furthermore, foliar fertilization improves fruit quality by increasing sugar content and enhancing transportability and shelf life [20].

Compared to other nutrients, calcium deficiency is less pronounced; nevertheless, it can lead to nutritional imbalances, manifesting in various ways depending on environmental factors and production conditions. Deficiency symptoms typically appear in young plants, affecting the roots, stems, and leaves. Roots become coated in a mucilaginous substance, while young stems and leaves exhibit deformities, often accompanied by a brownish-yellow discoloration along the margins. Under drought conditions combined with extreme temperatures, calcium deficiency can lead to pollen sterility, widespread flower abortion, and a reduced fruit-setting capacity. Fruits, including those that are still green, may develop blackening at the tip (Fig. 13). An

excess of calcium can inhibit the uptake of certain micronutrients, specifically iron, manganese, magnesium, and potassium, with which it maintains an antagonistic relationship.



Fig. 13. Symptoms characteristic of calcium deficiency

Sulfur is an important element for plants; it is widely distributed in nature and is absorbed by plants through their root systems, primarily in the form of SO_4^{2-} ions, which are subsequently transported and utilized in the synthesis of sulfur-containing compounds [31]. In small quantities, this element can also be taken up through the leaves from the atmosphere in the form of SO_2 oxides; however, high concentrations of this form of sulfur in the air can cause toxicity.

Sulfur is required by plants from the very early stages of growth for the synthesis of sulfur-containing amino acids and proteins. Certain compounds synthesized through sulfur metabolism help counteract the negative effects of abiotic stress caused by the presence of free radicals within the plant [17]. Sulfur deficiency is less common than deficiencies in nitrogen, phosphorus, or potassium. Nevertheless, in cases of severe sulfur insufficiency, plant growth is stunted, and leaves remain small, exhibiting a greenish-yellow to whitish coloration due to a reduction in chlorophyll content. Sulfur deficiency resembles nitrogen deficiency; however, because sulfur has limited mobility within the plant, it is not translocated from mature leaves to younger ones. Deficiency symptoms first appear on young leaves and gradually spread toward the base of the plant (the reverse of the pattern seen with nitrogen). The leaf veins appear lighter in color

than the rest of the leaf (Fig. 14)

High concentrations of sulfur oxides in the atmosphere accelerate plant aging, cause necrosis of leaf tissues, and reduce the ascorbic acid content in fruits. During prolonged droughts, the concentration of sulfur oxides in the atmosphere increases significantly;

when these are absorbed by light precipitation, they can lead to acid rain and various forms of toxicity in plants.



a. sulfur **b.** magnesium

Fig. 14. Symptoms characteristic of sulfur and magnesium deficiency

Magnesium is recognized as an essential element for plant growth and development, as it is a component of chlorophyll and plays a role in balancing plant nutrition, particularly in relation to nitrogen and potassium. Indirectly, magnesium influences fruit quality, as well as the suitability of the fruit for storage and transport.

Due to its high mobility, magnesium facilitates the uptake and translocation of phosphorus within plants; there is a positive correlation between phosphorus and magnesium content in various plant tissues. Furthermore, in conjunction with potassium, magnesium helps regulate cell turgor. A magnesium deficiency leads to a reduction in chlorophyll content, which in turn diminishes the rate of photosynthesis and overall productivity.

Symptoms of magnesium deficiency occur primarily in indeterminate varieties grown in greenhouses on acidic substrates characterized by low potassium and excess calcium levels. Because magnesium is highly mobile within the plant, much like nitrogen, it migrates from mature leaves to younger ones; consequently, when the element is in short supply, deficiency symptoms first appear on the mature leaves. Such deficiencies are most frequently observed when tomatoes are grown in greenhouses or polytunnels, resulting in stunted growth and the appearance of chlorotic spots between the leaf veins. Symptoms of magnesium deficiency manifest as discoloration in the areas between the leaf veins, which turn light green to yellowish due to a reduction in chlorophyll content, while the veins themselves remain green. In some cases, leaf deformations occur, along with localized swellings between the veins and the development of orange or purple coloration. Subsequently, necrosis may appear in the affected areas of the leaves, which, in more severe cases, leads to the breakdown of the tissue.

Microelements are nutritional components that plants require in very small quantities for normal growth and development. When tomatoes are grown in open fields, the plants' requirements for manganese, iron, copper, zinc, boron, and molybdenum are

generally met by the levels of these elements already present in the soil [7]. Initially, symptoms resulting from a deficiency or an excess of a specific element are very difficult to detect. Disruptions in plant growth and development caused by a lack of microelements occur more frequently when tomatoes are cultivated in artificial substrates.

Manganese and boron play a particularly important role in the synthesis of carbohydrates and in the initiation of reproductive organ formation and fruit set; zinc, meanwhile, is essential for regulating respiratory processes and synthesizing auxins. The deficiency of any given microelement in tomato plants manifests differently throughout the growing season, though the severity of the impact varies depending on the specific physiological stage.

Boron is involved in regulating the plant's water balance and in mitigating the toxicity of other elements present in the soil solution or artificial substrate. A boron deficiency leads to the necrosis of meristematic tissues (Fig. 15), most notably in the apical buds—as well as the shedding of flower buds, blossoms, and young fruit.



Fig. 15. Shedding of flower buds caused by a boron deficiency

In plant nutrition, the limited availability of an element dictates the course of physiological processes and crop yield. **Iron** is an essential element that can become unavailable to plants, particularly in calcareous and alkaline soils, leading to various physiological disturbances. The primary visual symptoms of iron deficiency in plants include the yellowing of leaves, or chlorosis, resulting from a decline in chlorophyll content; this occurs because iron serves as an essential cofactor for chlorophyll synthesis. Since iron is not translocated to other plant organs, the deficiency manifests primarily in young leaves [23]. It presents as a discoloration of the leaf blade, which turns a whitish-yellow due to the reduction in chlorophyll, a condition similar to magnesium deficiency (Fig. 16).



Fig. 17. Characteristic symptoms of iron deficiency

Compared to other microelements, **manganese** is present in plants in larger quantities, particularly in the leaves, and to a lesser extent in the fruits. The manganese ion enhances plant resistance to drought by reducing transpiration. Manganese deficiency resembles that of iron or sulfur, though the discoloration of the leaves creates a more mottled, mosaic-like appearance. Leaf growth is stunted, and the foliage gradually turns a grayish-yellow, eventually developing necrotic spots [32 33,]. An excess of manganese can also cause physiological disorders, which may manifest as dark streaks along the leaf veins and the deformation of fruits.

Copper plays an important role in plant metabolism. Within the leaves, it is located in the chloroplasts. Together with other microelements, it participates in metabolic reactions and contributes to maintaining the balance between carbohydrates and proteins; it also promotes an increase in the content of sugars and vitamins. Copper prevents the physiological aging of leaves, thereby prolonging their photosynthetic activity.

Copper deficiency leads to disruptions in the synthesis of amino acids and proteins. Tomatoes exhibit moderate sensitivity to an excess of copper. In more pronounced cases, this causes the atrophy of the root system and color changes in the leaf tissue between the veins, at supra-optimal levels, this phenomenon manifests as a chlorotic, pale-green appearance.



Fig. 17. Characteristic symptoms of copper deficiency

Certain hues, caused by anthocyanins, may appear on some leaves, especially when an excess of copper is accompanied by an excess of other microelements, such as manganese or zinc. In cases of more severe toxicity, copper can lead to the premature drying of the leaves (Fig. 17).

Although zinc is present in plants only in small quantities, it plays an important role in the synthesis of several enzymes and the regulation of respiratory processes [38]. it also exerts a positive influence on chlorophyll formation and the fruit-setting process. Visual symptoms of zinc deficiency may appear when tomatoes are grown in calcareous (carbonate-rich) soils, a condition exacerbated by the application of high doses of phosphorus, and manifest as interveinal chlorosis (discoloration of the leaves between the veins), the formation of short internodes, small leaves arranged in a rosette pattern, and the development of deformed fruit (Fig. 18).

Along with other microelements, molybdenum is of major importance for the balanced nutrition of tomatoes, particularly when they are cultivated in acidic soils or substrates. A deficiency in molybdenum leads to the accumulation of nitrates within the plant's tissues. Under conditions of insufficient molybdenum, characteristic symptoms emerge, including leaf discoloration, stunted growth, and reduced fruit production.



Fig. 18. Characteristic symptoms of zinc deficiency

Physiological disorders in plants can also arise from the improper use of pesticides. These disorders depend on factors such as the type of herbicide, the active ingredient, the dosage, the application conditions, and the plant's developmental stage. In some instances, it is difficult to determine whether the observed symptoms are caused by herbicide exposure, seed quality issues, or a viral infection. It is also common for pesticides applied to a preceding crop to have a residual effect; residues remaining in the soil can significantly impair plant growth and productivity

4. Conclusions

(1). Difficulties in plant growth and development can arise from factors other than infectious con-tamination. During the growing season, tomatoes are often exposed to unfavorable environmental conditions, such as extreme temperatures, insufficient or excessive light, and moisture deficits, which, either individually or through complex interactions, can lead to physiological disorders with serious consequences for yield quantity and quality.

(2). Tomatoes are sensitive to soil acidity and compaction levels. Reduced porosity combined with excess soil moisture leads to root asphyxiation. Prolonged asphyxiation can trigger symptoms re-sembling various nutrient deficiencies—such as those of phosphorus, magnesium, or nitrogen—thereby increasing the plants' vulnerability to infectious diseases.

(3) Nutrient deficiencies or excesses cause various physiological disorders that impact plant vigor and resistance, as well as productivity levels and fruit quality. Assessing plant nutritional status based on visible symptoms is a primary, subjective method of evaluation. This assessment relies on identifying states of deficiency or toxicity

manifested through specific signals on plant or-gans—signs that vary according to the specific nutrient, the nature of the manifestation, the bio-logical characteristics of the variety, and crop management conditions.

(4). Accurately diagnosing nutritional imbalances and specific nutritional needs is crucial for opti-mizing nutritional regimens, regulating tomato plant growth and development, and applying sup-plementary fertilizers; such measures help mitigate the impact of environmental stressors (light, temperature, humidity, air composition) while simultaneously strengthening the plants' resistance to various pathogens.

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