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REVIEW

Coffee plant diseases affected by nutritional balance

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ABSTRACT

In recent years, ambiental sustainability has become a priority in agricultural production programs throughout Brazilian territory due to the need to ensure food security and environmental quality. Diseases continue to be a factor limiting sustainable agricultural production, due to the great need for chemical defenses for their control. Thus, it is indispensable to make use of alternative management techniques to reduce the use of such chemical defenses and to increase resistance of plants to diseases. It is known that nutritional balance affect plant resistance to diseases, and effective physical and biochemical response of plants to pathogens is determined by adequate concentrations of mineral elements in the plant tissues. This review presents the most recent information related to the mode of action of the nutrients in the host-pathogen interaction and individual action in the control of plant diseases with the use of essential nutrients, as well as other elements considered beneficial, such as silicon. It also reports on the use of some of these mineral nutrients in control of the main diseases of the coffee plant that occur in Brazil, especially rust, cercosporiosis, phoma leaf spot, and bacterial blight. In addition, contradictory results are found in the literature on the use of mineral nutrients in control of different diseases, including coffee diseases.

Key words: Coffee growing; nutrients; management; pathogens; plant physiology.

1 INTRODUCTION

Some factors can reduce the quantity and quality of coffee beans harvested, including climate, soil fertility, plant nutrition, diseases and pests. To control coffee diseases in Brazil in recent years, the use of resistant varieties has been implemented as a long-term measure. However, the introduction of these materials in coffee fields is still slow, and thus the use of fungicides continues to be important in diseases control. In the field, protective and systemic fungicides are generally applied, generally composed of a mixture between triazoles or carboxamides with strobilurins (Pozza; Pozza, 2012; Pozza, 2021). However, Brazilian coffee growing is one of the most demanding in relation to social and environmental sustainability. Consequently, the demand regarding reduction in the use of agricultural chemicals should be followed according to environmental legislation, with the aim of forests conservation and native fauna, and protection of water resources of workers and of consumers (Resende et al., 2022a).

Thus, correct and balanced fertilization is not only essential for the growth and development of the plants, but is also considered a primary component for complete expression of the genetic resistance of the plants, seeking to constitute their resistance barriers (Huber; Haneklaus, 2007). The plant nutrition is fundamental in control of plant diseases and is the basis of resistance. The phenotype of resistance is simply the genotype by environment interaction. Expression of genes, including those associated with the physical or chemical resistance barriers, depends on the balanced presence of nutrients and on water. Otherwise, it is quite likely that the DNA will not even uncoil from the histones and open its double helix for synthesis of messenger RNA (Pozza; Pozza, 2012). That makes the "gene" inoperative and the plant susceptible to infection by pathogens. According to these same authors, at ideal concentrations, nutrients reinforce physical and chemical barriers that constitute resistance, and these factors are important in the plant-disease interaction.

The effect of nutrients on plant physiology should be studied in an individual manner, that is, there should not be a standardized preconception. The action of each element in the coffee plant-disease interaction will depend on its concentration and on the form available in the plant tissues. One particular nutrient can reduce infection from a determined pathogen in coffee, but increase by another, depending on the species studied. Thus, response to diseases is specific and is subject to the causal agent (fungus, bacteria, nematode, or virus). Then, it is necessary to use adequate crop practices so as to improve the availability, uptake, distribution, and use of the nutrients in the plants. According to Huber and Haneklaus (2007), Uchôa et al. (2011), and Freitas et al. (2015a,b), both physical and chemical characteristics of the soil and of the coffee plant affect interaction of the nutrients, including the amount of organic matter, water availability and irrigation management, soil texture and structure, pH, the number of plants per hectare, the way the plant is grown, and climate effects. Remembering that water is very important in the process of absorption of nutrients by the coffee tree. Without water, there is no transport, translocation, or absorption of nutrients by plants.

Therefore, the function of each element should be understood as part of a balanced system, interdependent on the genome of the host or of the coffee plant and the environment, with the aim of establishing the balance of nutrients to obtain maximum yield in each harvest. Considering the above, the aim of this review is to focus on how adequate nutrition can affect physiological processes to establish and implement resistance barriers capable of affecting the intensity coffee diseases.

2 NUTRIENTS IN THE CONSTITUTION OF RESISTANCE BARRIERS AGAINST PATHOGENS

Morphophysiological processes affected by specific nutrients that condition reactions to increase plant resistance to diseases, including the coffee plant, are generally not known (Marschner, 2012). Various studies have documented the speed and the extension of plant defense reactions, often decisive for the success or failure of the infection, as not exclusively under genetic control but affected by mineral nutrients or climate variables (Dietrich; Ploβ; Heil, 2004).Thus, resistance, especially that against various isolates or races of the pathogen, also called horizontal resistance, can be increased by three mechanisms, namely, i) anatomical alterations, for example, greater lignification and/or silification, ii) biochemical and physiological changes leading to the concentration of nutrients in specific locations and high production of repellent or inhibitory substances, and iii) restriction of the transfer of nutrients to the pathogens, impeding their growth and development (Agrios, 2005; Marschner, 2012; Huber; Römheld; Weinmann, 2012).

2.1 Anatomical changes (physical resistance barriers)

Lignin biosynthesis and deposition on secondary cell walls are processes programmed during the growth and development of plants, and this is generally understood as a mechanism to increase the physical barriers against initial colonization of the pathogens (Bonello et al., 2003; Miedeset al., 2014). In the literature, N deficiency is reported as inducing expression of genes related to lignin biosynthesis (Bhuiyan et al., 2009). Lignification of infected cells impedes the propagation of hydrolytic toxins and enzymes from the pathogen to within the host and, at the same time, avoids the transfer of water and nutrients from the plant cells to the pathogen (Smith et al., 2007).

The effect of N on diseases is widely described; however, the results are inconsistent and contradictory and the causes of these inconsistencies are little understood (Hoffland; Jeger; Van Beusichem, 2000; Huber; Thompson, 2007; Tavernier et al., 2007; Marschner, 2012). The cause of duality in the effect of N may be related to the form of N available to the hosts, the type of pathogen (whether obligate or facultative parasites), and the stage of development of the plant during N application (Dordas, 2008).

N available in the form of NH_4^+ increases the diseases intensity caused by *Fusarium*, *Rhizoctonia*, and *Sclerotium*. In contrast, *Pythium*, *Phymatotrichum*, and *Pseudomonas*are favored by N in the nitrate form NO_3^- (Snoeijers et al., 2000). The form of N can affect soil pH and the availability of other nutrients, such as Mn, and change the phenol and silicon (Si) content, which also affect resistance to diseases (Dordas, 2008).

In relation to the type of pathogen, the effect of N varies. The susceptibility of wheat to the biotrophic pathogen *Puccinia graminis* spp. *tritici*increases along with N supply (Kiraly, 1976). The anatomical and biochemical changes as a consequence of infection by this class of pathogens and the increase in concentration of low molecular weight organic compounds extracted by them are the main factors responsible for direct correlation of N supply and susceptibility to the biotrophic pathogens (Marschner, 2012). In contrast, the susceptibility of the tomato plant to the facultative parasite *Xanthomonas vesicatoria* reduces with an increase in N (Kiraly, 1976).

Nitrogen fertilization also increased the intensity of white mold (*Sclerotinia* spp.) in maize in two locations in the state of Minas Gerais (Dornelas et al., 2015). These authors observed linear increases in the area under the disease severity progress curve from 23.8% to 51.7% with an increase in N application from 20 kg ha^{-1} to 190 kg ha^{-1}. Moreover, this same increase in N also increased yield.

In addition to N, Si deposition in the epidermis can constitute a physical barrier of plant resistance (Figure 1). Si can accumulate in the epidermis, forming the cuticle-Si double layer, thus impeding penetration of the pathogen through a mechanical barrier (Cai et al., 2007). It is deposited as amorphous silica on cell walls and contributes to mechanical properties, including the rigidity and elasticity of the cell wall (Taiz; Zeiger, 2013; Moraes et al., 2006). The positive effect of Si on plants has been attributed to reduction in water loss due to cuticle transpiration, formation of Si deposits under the cuticle, reduction in apoplastic flow, and reduced uptake of toxic minerals, due to the formation of Si deposits on the roots (Romero; Munévar; Cayón, 2011). Due to the increase in rigidity and resistance of the plant cell wall. A wax layer stimulated by silicon also forms, which is able to decrease water loss and reduce the cercosporiosis (*Cercospora coffeicola*) incidence by 63% and its severity by 43% in coffee seedlings (Pozza et al., 2004). Although coffee is a dicotyledon, microanalysis of MAX X-ray and mapping for Si showed uniform distribution of the element across the entire abaxial surface of the coffee leaves in the varieties Catuaí, Mundo Novo, and Icatu treated with silicate in the soil for at least six months. In the leaves of the untreated plants, Si was rarely found. In the scanning electron microscope (SEM) images as well, a well-developed wax layer was observed on the lower surface of the leaves originating from all the treated plants, and this layer was thicker in Catuaí and rare or absent in the untreated plants (Figure 1).

Si improves the resistance of plants to diseases caused by fungi and bacteria. Two mechanisms are responsible for this improvement. The first consists of activation of Si as a physical barrier (Figure 2). It is deposited below the cuticle to form the cuticle-Si double layer (Yamaji et al., 2008). This layer mechanically impedes penetration by fungi and pests. The second mechanism explains the activation of soluble Si as a modulator of the resistance of hosts to pathogens (Belanger; Benhamou; Menzies, 2003). Different studies on rice, wheat, and cucurbits have shown increases in production of phenols, lignin, H_2O_2, and phytoalexins from Si supply, and these compounds are responsible for responding to infection upon degrading the cell walls of fungi and bacteria (Sun et al., 2010).

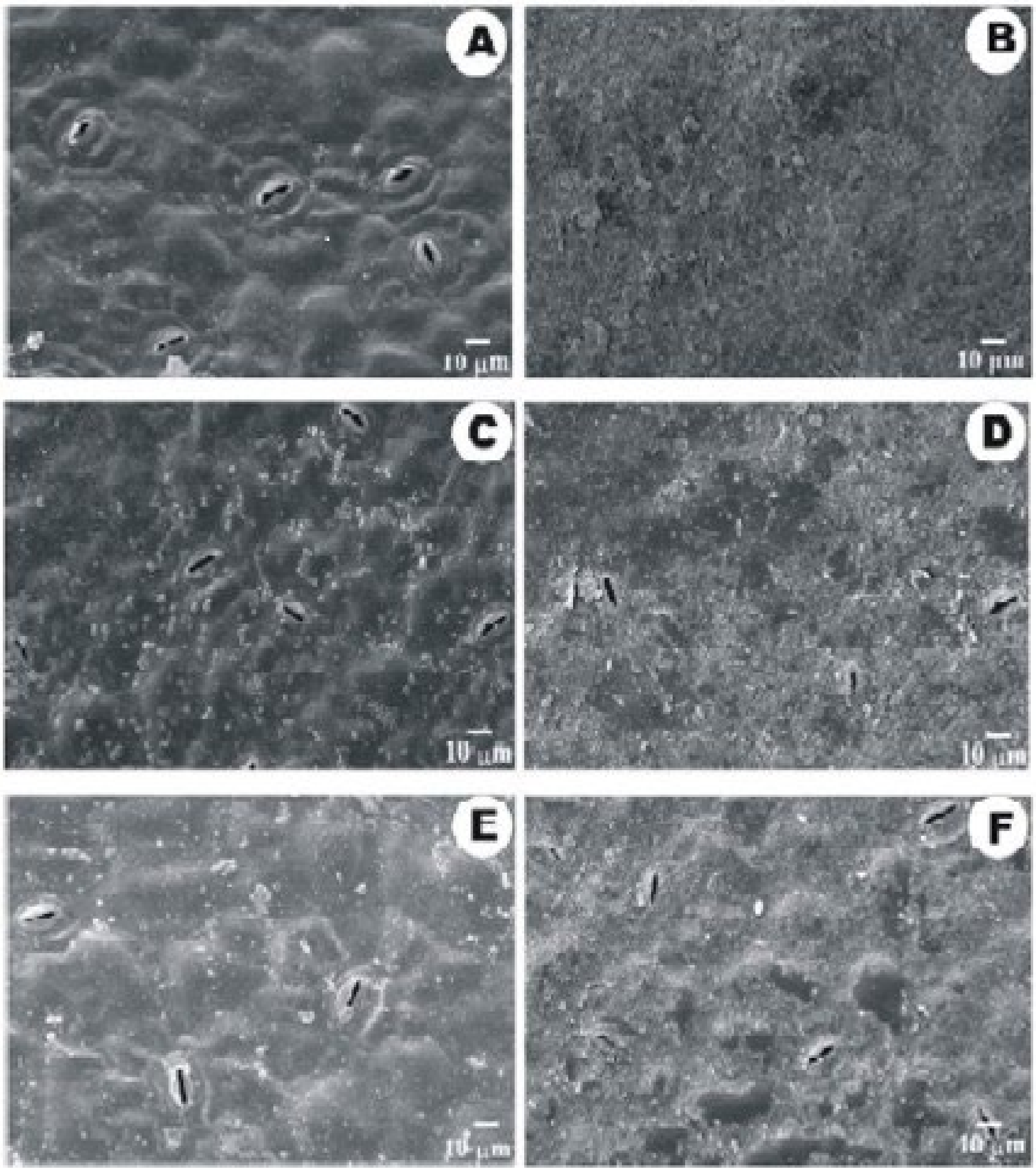

Figure 1: Lower surface of leaves of coffee plants (*Coffea arabica*) of the varieties Catuaí (A-B), Mundo Novo (C-D), and Icatú (E-F), treated with $CaSiO_3$ (B, D, and F) and untreated (A, C, and E). (Pozza et al., 2004).

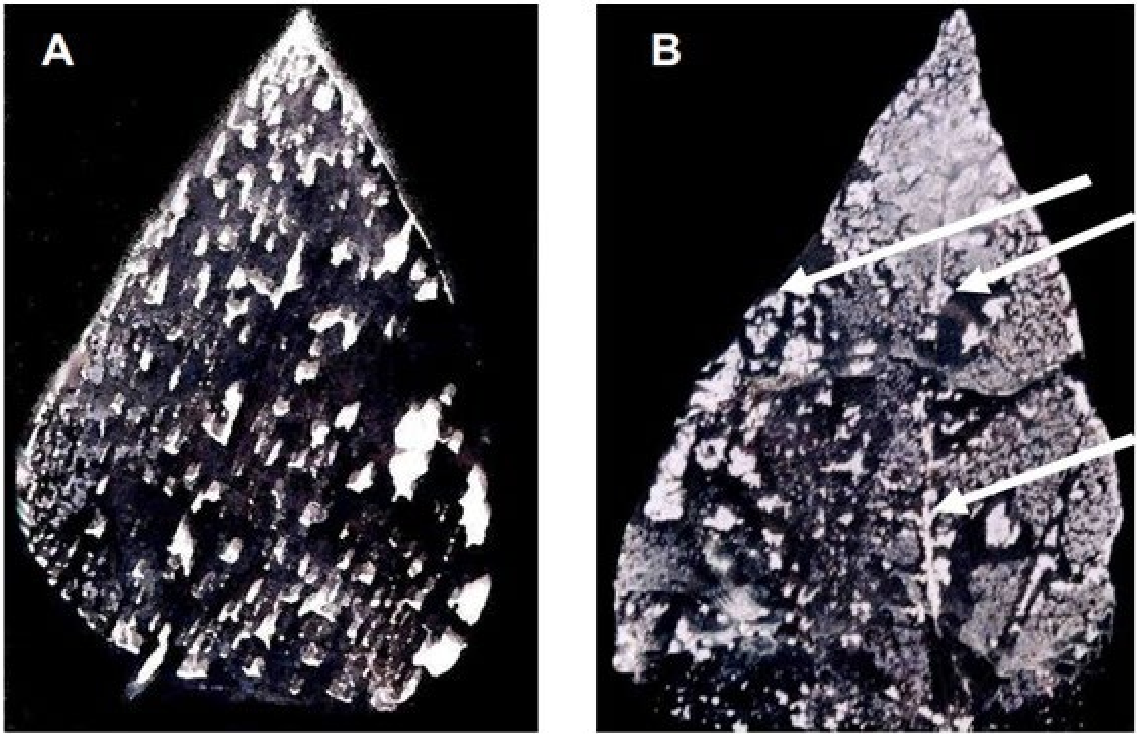

Figure 2: Spodogram of dry bean leaves. A: accumulation of silicon in plants not treated with the element; B: plants treated with 1.89 g $kg^{-1}$of silicon (Moraes et al., 2009).

Calcium silicate has promoted formation of a physical barrier to prevent the occurrence of anthracnose in dry bean (Moraes, et al., 2009). According to the spodogram, the greatest accumulation of silicon (whiter parts of Figure 2B) was in the dry bean leaf through leaf application of sodium silicate, especially in the leaf veins, the main region of occurrence of anthracnose in dry bean, contrasting with the leaf without silicon (Figure 2A).

In coffee seedlings, there was a linear decrease of 10.8% in the percentage of plants with cercosporiosis from the increase in SiO_2 rates applied to the substrate (Figure 3A). At the highest silicon application rate (1.26 g kg^{-1} of substrate), the lowest number of diseased plants occurred. In this study, the effect of sodium silicate alone was observed on total reduction of lesions per plant (Figure 3B). The lowest total number of lesions was obtained at the application rate of 0.84 g kg^{-1} of substrate.

The application of Si also reduced the soybean rust intensity (Lima et al., 2010a). With the increase in Si in the nutrient solution, a smaller area under the number of lesions progress curve of (AUPCNL) was observed. The plants supplied with 280 mg L^{-1} Si had 24.3% less AUPCNL in relation to those grown without the addition of Si (Figure 4). Application of Si for control of various diseases has been reported, diseases such as brown spot (*Cochliobolusmiyabeanus*) and sheath blight (*Thanatephorus cucumeris*) in rice; and application of Si also increased resistance to various pasture pathogens (*Rhizoctonia solani*, *Pythium*spp, *Pyriculariagrisae*) (Zhang et al., 2006). In dry bean, leaf application of sodium silicate reduced anthracnose severity by 62% in relation to inoculated plants without silicate (Moraes et al., 2006).

Using geostatistical modeling, Freitas et al. (2015a) correlated spatial distribution of yellow sigatoka with soil fertility and mineral nutrition of the banana plant. According to kriging maps, the highest rates of disease infection were found in areas with high sand content; and conversely, in areas of soil with high silt and high organic matter, the lowest rates of progress (r) of sigatoka were found. Soils with high sand content have less water and nutrient holding capacity. Analyzing the fertility of soils with high silt content, the kriging maps showed higher Ca concentrations, thus confirming the importance of this nutrient in management of plant diseases.

High concentrations of Ca, though in balance with other nutrients, drastically inhibit the action of polygalacturonases (Bateman; Lumsden, 1965). However, excess of this nutrient also causes competitive inhibition with other elements, such as K and Mg, leading to cation imbalance in the cytoplasm (Marschner, 2012). Linear reduction in leaf K content with the application of Ca was observed by Pinheiro et al. (2011) for soybean rust in nutrient solution (Figure 5). Nevertheless, there was reduction in Ca and K content when K and Ca, respectively, were added to the nutrient solution, corroborating the hypothesis of antagonism or competition between these cations. Under low concentrations of Ca, there is an increase in susceptibility to pathogens of the vascular system. These

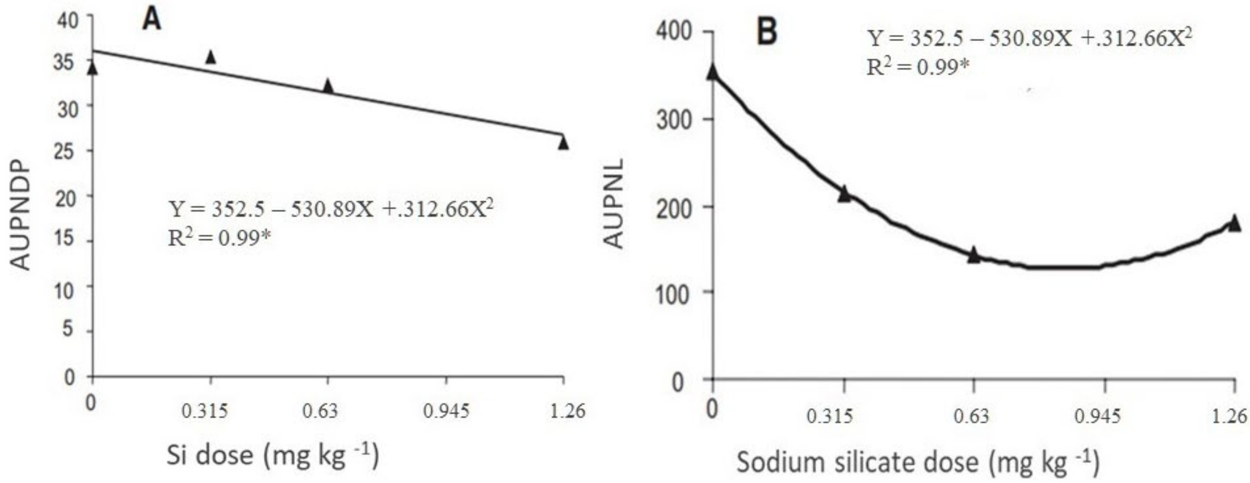

Figure 3: Area under the progress curve of number of diseased plants (AUPNDP) (A) and area under the progress curve of total number of lesions (AUPNL) (B) for brown eye spot of coffee (*Coffea arabica*) according to increasing doses of silicon applied to the substrate (Santos Botelho et al., 2005).

pathogens invade the xylem and dissolve the cell walls of the vascular cylinder, leading to the appearance of symptoms typical of wilts. Plant tissues with low Ca content are more susceptible to post-harvest and storage diseases compared to tissues containing normal content of Ca (Dordas, 2008).

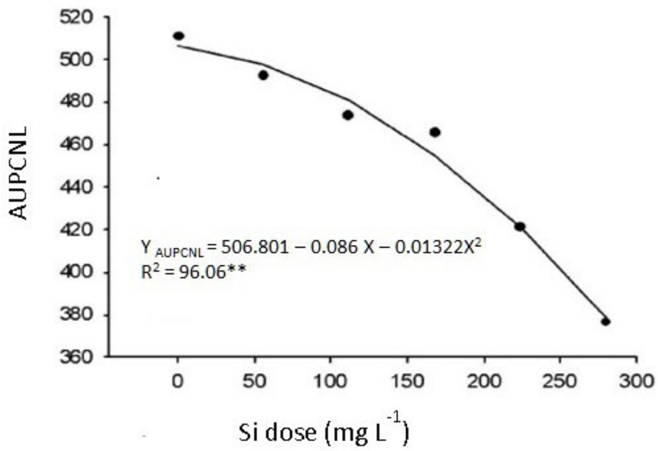

Figure 4: Area under the progress curve of number of rust lesions (*Phakopsora pachyrhizi*/ cm^2) progress curveof leaf area (AUPCNL) of soybean plants (*Glycine max*) according to increasing application rates of silicon in the nutrient solution (Lima et al., 2010a).

2.2 Biochemical alterations (biochemical resistance barriers)

Biochemical and physiological changes can lead to the concentration of nutrients in specific locations; for example, modifications in the Ca/K pump can change the direction of flow of these nutrients in the asymptomatic and symptomatic tissues under various coffee diseases (Figure 6). In the study

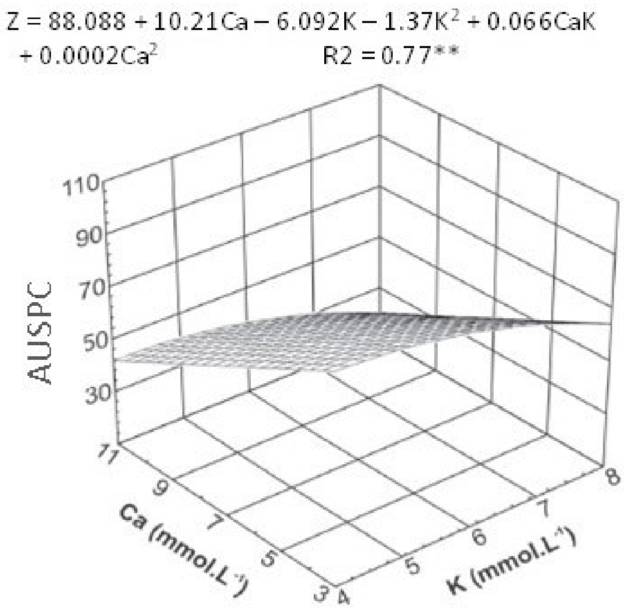

Figure 5: Area under the progress curve of the severity (AUPCS) of soybean rust (*Phakopsora pachyrhizi*) according to application rates of potassium and calcium in nutrient solution (Pinheiro et al., 2011).

of Belan et al. (2015) on asymptomatic tissues and on tissues with symptoms of coffee leaf rust and blister spot, the flows of Ca and K remained constant, with little loss of K in the areas with lesions. In symptomatic tissues, unlike, inversions in the Ca content were observed, which increased in the areas with lesions, due to the concentration of Ca at the location to attempt to structurally restrict advancement of the lesions of the bacterial blight, phoma leaf spot, and cercospora leaf spot pathogens (Figure 6). The activity of some pectolytic enzymes is strongly inhibited by Ca^{2+}, which explains the strong positive correlation between the Ca concentration in the tissues and resistance to fungal and bacterial diseases (Huber; Römheld; Weinmann, 2012). Induced resistance mechanisms are associated with the type of pathogen and resistance of the host, as well as the nutritional state of the plant. Pectolytic enzymes of parasites not only dissolve the middle lamella but also break the permeability of the plasmatic membrane and increase the K^+ efflux and H^+ influx, which lead to hypersensitivity reactions, such as localized necrosis (Atkinson; Baker; Collmer, 1986). In another pathosystem, such as leaf spot (*Helminthosporium cynodontis* Marig.), fungal toxins increase the K^+ efflux and thereby deplete cells and infected tissues of K. Thus, the severity of disease symptoms (leaf spotting) is negatively correlated with K concentration in the leaves (Richardson; Croughan, 1989). That is, the flow of Ca from healthy cells to symptomatic ones and Kin the opposite direction, must exist to likewise trigger the synthesis of pathogenesis-related (PR) proteins, linked with the constitution of resistance barriers. Consequently, it is necessary and paramount that these nutrients be present and in balance in the cytoplasm. However, more studies are necessary to investigate the expression of these proteins linked with the balance and the amounts of these nutrients.

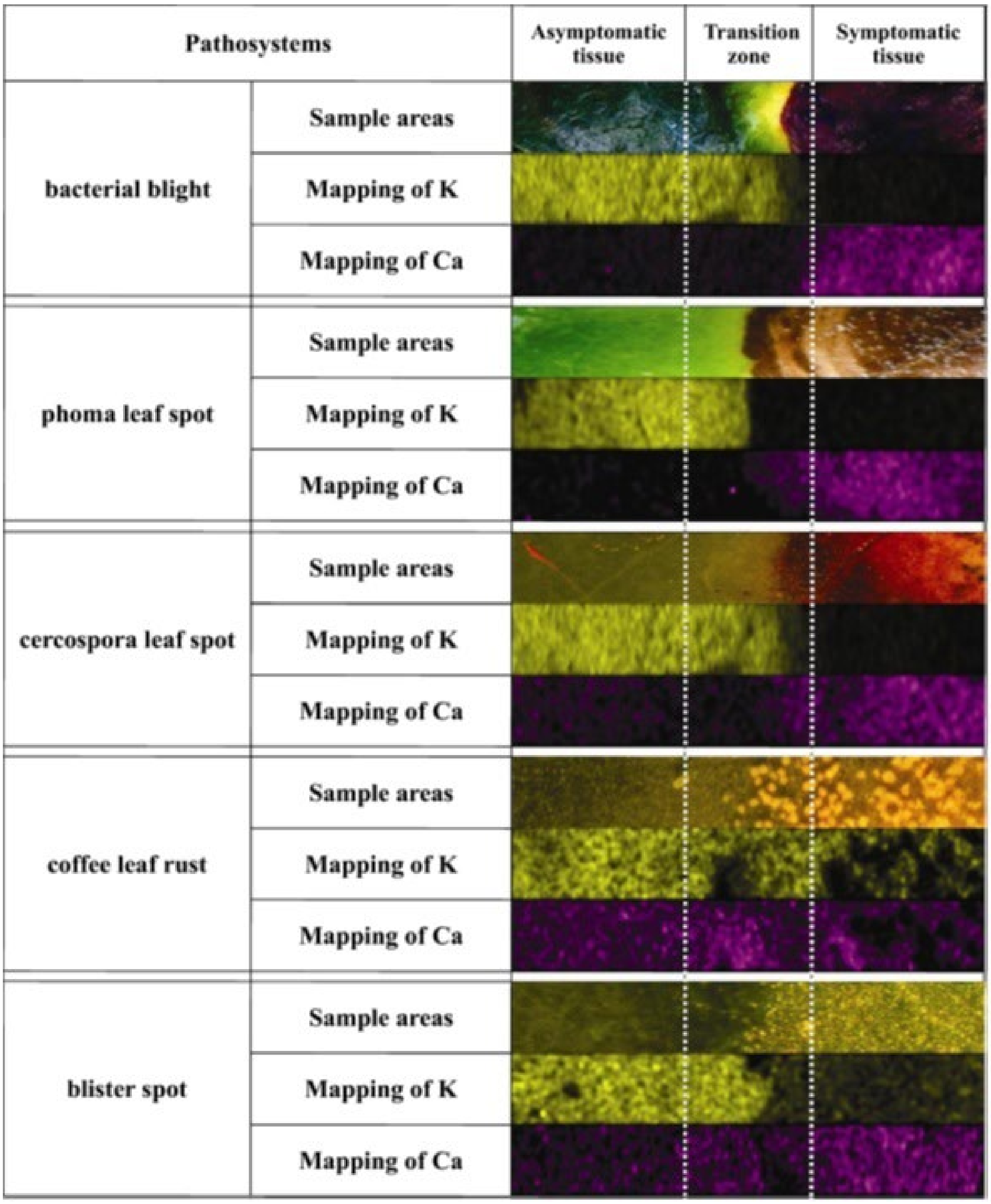

Figure 6: X-ray microanalyses for mapping potassium (K) and calcium (Ca) in diseased tissues of coffee (*Coffea arabica*) leaves: bacterial blight (*Pseudomonas syringae*pv*garcae*), phoma leaf spot (*Phoma tarda*), cercosporiosis (*Cercospora coffeicola*), rust (*Hemileia vastatrix*), and bitter rot (*Colletotrichum gloesporioides*) (Belan et al., 2015).

Biochemical compounds are synthesized when the receptors of the plant cells recognize the pathogen (Newman et al., 2013). These secondary metabolites protect the plants against infections by pathogenic microorganisms and have been divided into three chemically distinct groups: terpenes, phenolic compounds, and nitrogen compounds (Taiz; Ziger, 2013).

Phosphorus is indispensable in terpene biosynthesis. The function of P in disease resistance is variable and inconsistent (Kiraly, 1976). P seems to be more effective in diseases management of fungal etiology in seedlings in which the development of vigorous roots allows escape from pathogens. Such was the case in a study of Barbosa Junior et al. (2017) on coffee rust according to different management practices of irrigation and of phosphate fertilization in a coffee field with drip irrigation. The absence of fertilization with phosphorus led to greater progress of coffee rust in the field. In that study in 2013 and 2014, for the treatments that were not irrigated and without phosphorus fertilization, the highest incidences were observed, reaching 27.43% and 77.43%, respectively. According to Walters and Murray (1992), resistance is based on release of elicitor compounds of the plant cell walls or when localized cell death begins, known as a hypersensitivity response.

Coffee yield variation in the field can be learned to obtain useful information for coffee management. Machine learning algorithms were evaluated to determine Arabica coffee yield. The use of the random forest model enabled to detect the most important variables for predicting coffee yield, as well as to identify how the nutritional status of the plants, such as Mg, Fe and Ca contents can be balanced to maximize yield. Variables related to the coffee nutritional status were more important than remote sensing variables for estimating coffee yield in the field. In general, Mg leaf content was the most important variable for yield class prediction in both the 2005 and 2006 harvests by the rf model. The CART algorithm defined Mg leaf content threshold <3.615 g kg^{-1} in 6/15/2005 for yield classification in the first node and this threshold obtained is consistent with the available literature associated with high coffee yields between 3.6 and 4.0 g kg^{-1} (Alves et al., 2022).

The micronutrients manganese, copper, iron, cobalt, and boron are involved in the metabolic pathway for biosynthesis of phenolic compounds, including quinones, tannins, and flavonoids (Graham; Webb, 1991; Pozza; Pozza, 2012; Pozza et al., 2004). The effect of manganese on expression of resistance to diseases of the root system and shoots has been extensively described (Heckman; Clarke; Murphy, 2003). Resistance associated with Mn applications is explained in terms of activation of the peroxidase and polyphenol oxidase enzymes, which increase the concentrations of phenols in the roots (Kalim et al., 2003). In addition, Mn is responsible for controlling biosynthesis of lignin and suberin through activation of enzymes involved in the shikimic acid and phenylpropanoid pathway (Marschner, 2012). Mn concentrations superior to the physiological demand of the plant can cause alterations in the proteome and metabolome of the apoplast of the leaf and, consequently, affect infection by pathogens. With the increase in Mn, an increase was observed in the expression of pathogenesis-related (PR) proteins, including glucanases and chitinases (Fecht-Christoffers, 2003), as well as improvement in the consumption and production relationship of H_2O_2 – peroxidases within the apoplast of cowpea leaves (Fecht-Christoffers et al., 2006; Führset al., 2009). In relation to the pathogen, Mn inhibits the induction of aminopeptidase. This enzyme provides amino acids essential for growth of fungi and pectin methylesterase, the function of which is related to degradation of the cell walls of the host (Dordas et al., 2008).

Another micronutrient, B, is directly involved in the maintenance and stability of the cell wall and has a beneficial effect on reduction of disease severity (Cookson; Pham, 1995; Kartal; Yoshimura; Imamura, 2004; Dordas et al., 2008). Nevertheless, the physiological mechanisms involved in inhibition of pathogen growth are not well understood. Bowen and Gauch (1966) observed inhibition in the growth of *Saccharomyces cerevisae*and *Penicillium chrysogenum*when supplied with high concentrations of B. The enzyme aldolase has been suggested as the target of high levels of B, making the fungi unable to efficiently use the carbohydrates to maintain the metabolic processes involved in their growth and reproduction. In grape, the effect of B on the fungus *Eutypalata* was determined by consumption mainly of non-cellulosic glucose of the hemicellulose fraction of the cell walls (Rolshausen et al., 2003).

Phenols are compounds with a double function, repelling and attracting different organisms in the plant environment. They act as protective agents, inhibitors, and toxic agents against phytopathogenic nematodes, bacteria, and fungi (Lattanzio; Lattanzio; Cardinali, 2006). According to Karou et al. (2005), phenolic compounds accumulate in plant tissues, mainly acting as phytoalexins. Thus, the synthesis, release, and accumulation of phenolic compounds, particularly salicylic acid, are fundamental for many plant defense strategies against pathogens (Bhattacharya et al., 2010).

These works produced several practical recommendations for coffee producers, such as, for example, the increase in nitrogen fertilization helps in the control of coffee tree cercosporiosis in the field, as well as the balance between calcium and potassium for this same disease.

2.3 Restriction in transfer of nutrients to pathogens

Restriction in transfer of nutrients and water supply is the main characteristic of vascular diseases as a consequence of penetration of pathogens through the root system, in the lateral roots, with subsequent colonization of the xylem vessels, leading to reduction in their function, with reflections on transpiration flow (Wheeler; Rush, 2001). After establishing themselves in the xylem, fungi and bacteria produce cellulolytic and pectolytic enzymes to degrade the cell wall of the parenchyma. As a result, the cytoplasm of the parenchymatous cells comes to constitute an obstacle to water and nutrient flow (Michereff et al., 2005). In addition, some pathogens of the vascular system are also able to oxidize and polymerize phenolic compounds. Under conditions of K deficiency, reduction in these compounds significantly declines.

The K present in the plants as the K^+ cation is required as a cofactor in more than 40 enzymes involved in respiration and in photosynthesis (Taiz; Zeiger, 2013). It is the main element in the establishment of cell turgor and in maintenance of cell electroneutrality (Mergel; Kirkby, 2001). This element promotes the development of thicker outside walls in the epidermal cells and determines patterns of stomatal opening. These two processes are closely related to lower intensity of diseases (Dordas, 2008).

In general, plants deficient in K are more susceptible to diseases compared to those that are adequately nourished. Perrenoud (1990) reviewed 2449 references of studies using K in crop plant health management and found reduction in the incidence of diseases caused by fungi of 70%, by bacteria of 69%, by insects and mites of 63%, by viruses of 41%, and by nematodes of 33%.

A greater area under the progress curve of yellow sigatoka (*Mycosphaerella musicola*) of the banana plant was found when K was omitted from the nutrient solution (Freitas et al., 2015b). The effect of potassium fertilization on management of black sigatoka (*Mycosphaerella fijiensis*) has also been confirmed. In the field, Uchôa et al. (2011) used geostatistical modeling to correlate the severity of this disease with soil fertility. According to the kriging maps that were generated, lower severity of the disease was observed in the areas with higher levels of K (57.5 mg dm^{-3}), and the highest severities were observed when the content of this nutrient was less than 28 mg dm^{-3}, reiterating the data of Freitas et al. (2015b), observed in a nutrient solution (Figure 7).

The susceptibility of plants deficient in K is due to change in the metabolic functions in the plant physiology (Cakmak, 2005). According to Huber and Graham (1999), low concentrations of K reduce the synthesis of high molecular weight compounds (proteins, starches, and cellulose) and increase the accumulation of low molecular weight organic compounds (amino acids), which are an easily available source of nutrients for the pathogens to colonize the plant tissues. In addition, their low concentration in the vacuole modifies the speed and time of stomatal opening, as well as water flow in the parenchymas, affecting penetration and colonization of pathogens.

Although low concentrations of K cause physiological disturbances, excess of this nutrient should be avoided so as not to compete with uptake of other cations, such as Mg and Ca (Marschner, 2012). Upon studying the effect of nitrogen and potassium fertilization on the severity of anthracnose in two maize cultivars, Carvalho et al. (2013) confirmed this cationic imbalance. Although the interaction of the lower N application rate (75 mg dm^{-3}) with the higher K application rate (1000 mg dm^{-3}) reduced the disease severity, a reduction was also found in the leaf Ca content with the increase in K. Application of N also had a negative effect on leaf content of K. In addition, the severity observed in the moderately resistant cultivar was 41% lower than that observed in the susceptible cultivar.

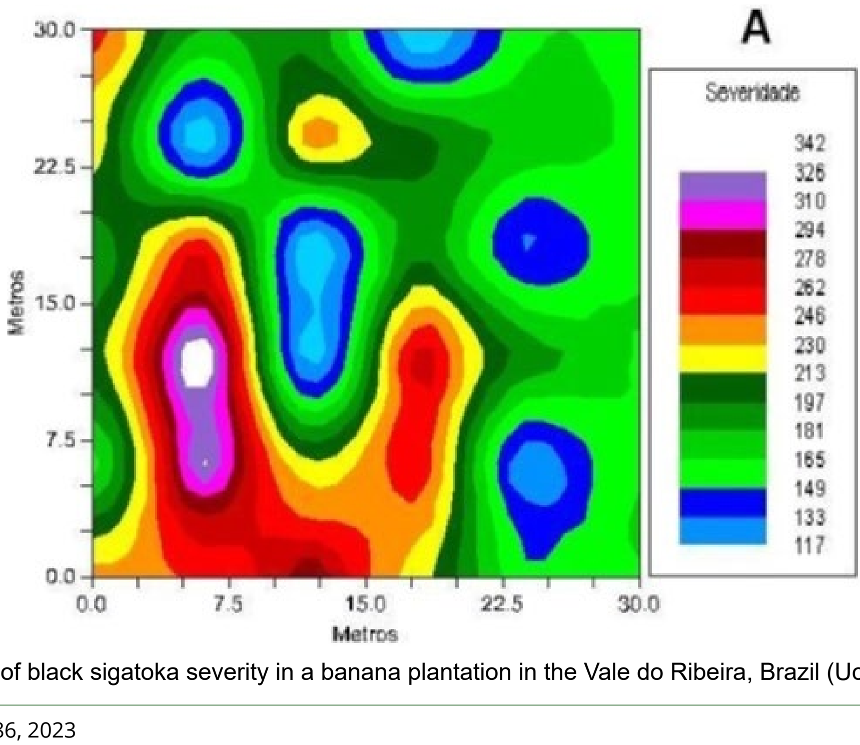

Figure 7: Kriging maps of black sigatoka severity in a banana plantation in the Vale do Ribeira, Brazil (Uchôa et al., 2011).

4 OTHER DEFENSE MECHANISMS RELATED TO PLANT MINERAL NUTRITION

4.1 Inhibition of advancement of the disease through accumulation of inhibitor compounds around the infection site or through direct contact with the nutrients

Nutrients are essential in various metabolic pathways involved in production of structural and/or biochemical defense mechanisms. Many compounds produced by secondary metabolic pathways are formed after the occurrence of infection and promote resistance to diseases; one of them is shikimic acid. These compounds are phytoalexins, flavonoids, and auxins, which are able to accumulate around the infection site, depending on the availability of various nutrients. Manganese, copper, iron, boron, and cobalt can be involved in the synthesis of various enzymes for synthesis of phenols, quinones, and lignin, with a function linked to plant defense.

Copper, for example, as a fungicide, its concentration is generally greater than 1250 mg/Kg or ppm. This amount is toxic to the leaf parenchyma, and for that reason should not be taken up. Thus, the product is used in formulations that are not absorbed through the leaf or are in low concentrations. The action of Cu as a fungicide is based on direct application on the surface of the plant and of the fungus concerned. Analyzing Cu from the nutritional perspective, in deficient plants, reduction was observed in synthesis of defense compounds, accumulation of soluble carbohydrates, and reduction in lignification, all of which contribute to lower plant resistance to diseases (Taiz; Zeiger, 2013).

In relation to nutrients that are able to increase resistance barriers, silicon and calcium can contribute significantly, as long as exposure time is provided for and sufficient amounts for the nutrients to be taken up. They are constitutive nutrients, and for that reason, they should be supplied through products with good solubility in the soil. In an integrated management study, the incidence of anthracnose in dry bean was reduced by 7% when the application rate of calcium silicate changed from zero to 1.89 g kg^{-1} of SiO_2on the ground. At the highest silicon application rate (1.89 g kg^{-1} of soil), there was the lowest area under the disease incidence progress curve (AUDIPC) (Figure 8A). The application at rates higher than those used could likely reduce even more the incidence of anthracnose in dry bean. The severity decreased by 35% with leaf application of copper. A linear reduction in disease was observed (Figure 8B). Thus, with the application of a higher dose of copper(78 mg L^{-1}), there was a smaller area under the progress curve of severity of anthracnose (Moraes et al., 2009).

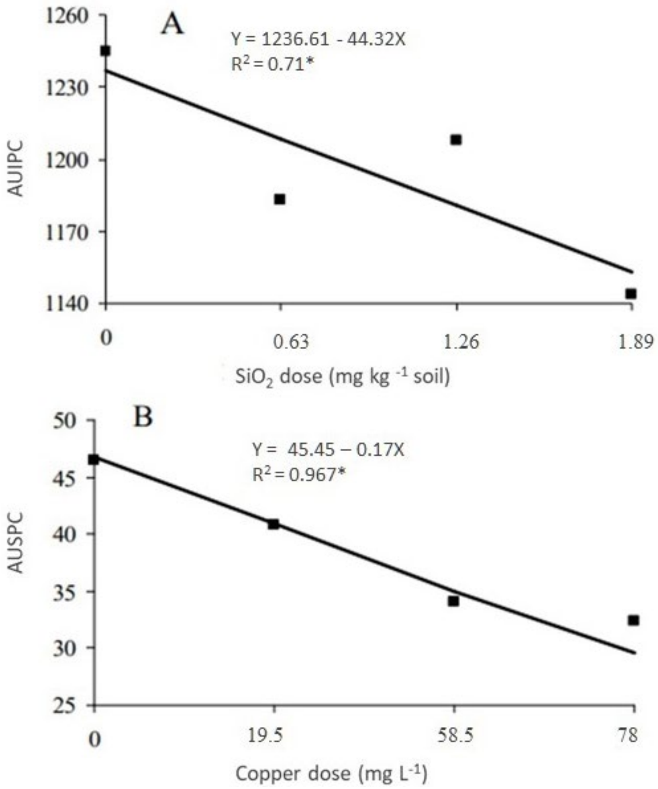

Figure 8: A: area under the disease incidence progress curve according to the application rates of calcium silicate applied through the soil; B: area under the disease severity progress curve according to the application rates of copper applied through the leaves (Moraes et al., 2009).

Another nutrient involved in reducing the intensity of diseases is sulfur. This element is found in amino acids (cystine, cysteine, and methionine) and is a constituent of various coenzymes and vitamins, such as coenzyme A, S-adenosyl methionine, glutathione, biotin, vitamin B_1, and pantothenic acid, which are essential to metabolism (Bloem et al., 2012). Most metabolic compounds containing S in their structure, together with the reactive oxygen species, are linked to recognition of the pathogen and to activation of plant response (Swarupa; Ravishankar; Rekha, 2014). Cisteine, for example, is directly linked to stress response as its function is related to acquired systemic resistance. Alvarez et al. (2012) studied the effect of a specific cytosolic cysteine and determined its presence to be obligatory to begin the immune response of the plant to the pathogen, and its connection to the hypersensitivity response was also proven.

Other studies also observed the direct antifungal mode of action of proteins rich in S, phytoalexins such as camalexin, elemental sulfur, and the degradation of products derived from glucosinolates (Williams et al., 2002, Williams; Cooper, 2004; Stec et al., 2004).

The toxicity of proteins rich in S, such as thiamine, is explained by their ability to generate ion channels in the cell membranes of the pathogens and consequently cause disturbances in the ion concentration gradient, affecting cell homeostasis (Hughes et al., 2000). The antifungal action of the $S^0$is due to its lipophilic character. The S^0 can enter directly through the cell wall of the fungus, causing disturbances in the redox reactions of the metabolism of the pathogen (Bloem; Haneklaus; Schnug, 2015).

Another micronutrient, zinc, can contribute to tolerance of plants to abiotic stress factors upon activating defense mechanisms through gene activation and regulation (Cakmak, 2000). However, applying Zn also reduces the severity of the diseases caused by biotic agents, as their effect is toxic through direct contact with the pathogens and is not subject to mediation in the metabolic reactions of the plants (Graham; Webb, 1991).

Plants take up zinc predominantly in the divalent form (Zn^{2+}) in soils with high pH (Broadley et al., 2012). Zn is involved in the metabolism of carbohydrates, in maintenance of the integrity of the cell wall, in protein synthesis, in regulation of auxin synthesis, and in pollen formation, and it contributes to respiration, photosynthesis, chlorophyll formation, etc. (Samant, 2009). The use of zinc sulfate in management of gummosis (*Lasiodiplodia theobromae*) of the peach tree inhibited the mycelial growth of this fungus and caused the formation of abnormal hyphae and swelling at the hyphal tips (Li et al., 2016). Chitin is the main polysaccharide of the cell wall of this fungus. The abnormal morphology of hyphae in the presence of Zn may be caused by chitin deposition, as found by Lanfranco et al. (2002). The mode of action of zinc sulfate against the fungus *L. theobromae* was also studied by Lew (2011). Zn ions at the concentration of 50 mmol L^{-1}destroyed the internal hydrostatic pressure of the cell and inhibited elongation of the hyphal tips of the fungus.

The application of Zn in the form $ZnSO_4.7H_2O$ in management of root rot (*Rhizoctonia* spp) in seedlings of guar bean (*Cyamopsis tetragonoloba* L.) resulted in an increase in plant resistance to the disease (Wadhwa et al., 2014). Increasing the concentration of Zn from 10 to 20 mg kg^{-1} led to an increase in the activity of antioxidant enzymes [polyphenol oxidase, peroxidase, phenylalanine ammonia lyase (PAL), and tyrosine ammonia lyase (TAL)]. Antioxidant enzymes perform an effective function against pathogen invasion. Peroxidase, for example, is involved in the synthesis of lignin at the pathogen penetration site. PAL and TAL play a key role in the metabolism of phenylpropanoid, whose synthesis is related to plant defense (Raghavendra et al., 2007; Kumar; Mali; Manga, 2010).

The effect of five doses (0.05, 0.25, 0.50, 1.0, 2.0 and 4.0 mg L^{-1}) of boron (B), zinc (Zn) and manganese (Mn) on the severity of rust on coffee plants grown in nutrient solution was evaluated by Pérez et al. (2020). Micronutrients were supplied to seedlings having two pairs of fully developed leaves. The seedling plants were inoculated with spores (106 mL^{-1}) of the coffee rust pathogen (*Hemileia vastatrix*). Five assessments of the severity of the rust symptoms were made starting on the 43rd day after inoculation. With B and Mn, there was a 15.1% and 52.3% reduction in severity of coffee rust at doses of 4.00 and 0.25 mg L^{-1}, respectively. With Zn there was a 78.0% decrease in area under the disease progress curve for severity (Figure 9).

The three micronutrients significantly affected the concentration of total soluble phenols (Figure 10), nevertheless, only Mn influenced the concentration of lignin (Figure 11). Boron, Zn and Mn all individually influenced the rust severity. However, the highest reduction in AUDPC of 78% was observed with the application of Zn at rates up to 2.00 mg L^{-1}. A similar rate of B reduced the AUDPC by 15%. The lowest AUDPC value for rust with Mn was observed at the intermediate rate of 0.25 mg L^{-1}. Manganese had a greater effect on the synthesis of total soluble phenols (TSP) and lignin in coffee seedlings inoculated with *H. vastatrix*. The results obtained in this research demonstrate the importance of a balanced mineral nutrition as a possible rust management strategy in order to reduce dependence on the use of fungicides and contribute to the sustainability of the coffee crop (Pérez et al., 2020).

Silicon also led to an increase in lignin in coffee seedlings. The addition of silicon to the substrate led to an increase in lignin content in seedlings in the nursery up to the dose of 0.52 g kg^{-1} of SiO_2 (Figure 12). At lower doses, the silicon may have been better distributed and was translocated to the leaves, leading to an increase in the amount of lignin in the leaves, which reduced the number of diseased plants.

4.2 Integration of crop management practices to improve plant nutrition, disease resistance, and crop yield

An increase in yield is expected when mineral nutrients are supplied in tropical crop systems. When nutrients are applied in an adequate manner, an increase in photosynthetic capacity is expected based on the increase in metabolically active elements in leaf tissues (Cai et al., 2007; Silva et al., 2010). Adding N, for example, stimulates photosynthetic capacity since most of the proteins of the Calvin cycle are constituted by N (Evans, 1989). P and K, in turn, increase the efficiency of the photosynthetic process.

Nutrients are intrinsic components of plant structure and metabolism, and their absence causes serious abnormalities in plant growth, development, and reproduction (Epstein; Bloom, 2005). When plants are infected by pathogens, their physiology is altered, especially the uptake, assimilation, and translocation of nutrients from the roots to the shoots, as well the use of these nutrients (Marschner, 2012). Some pathogens immobilize nutrients from the rhizosphere or from the infected tissues, such as the roots, whereas others interfere in the efficiency of translocation or use, causing nutritional deficiency or hyperaccumulation and, consequently, phytotoxicity (Huber; Haneklaus, 2007).

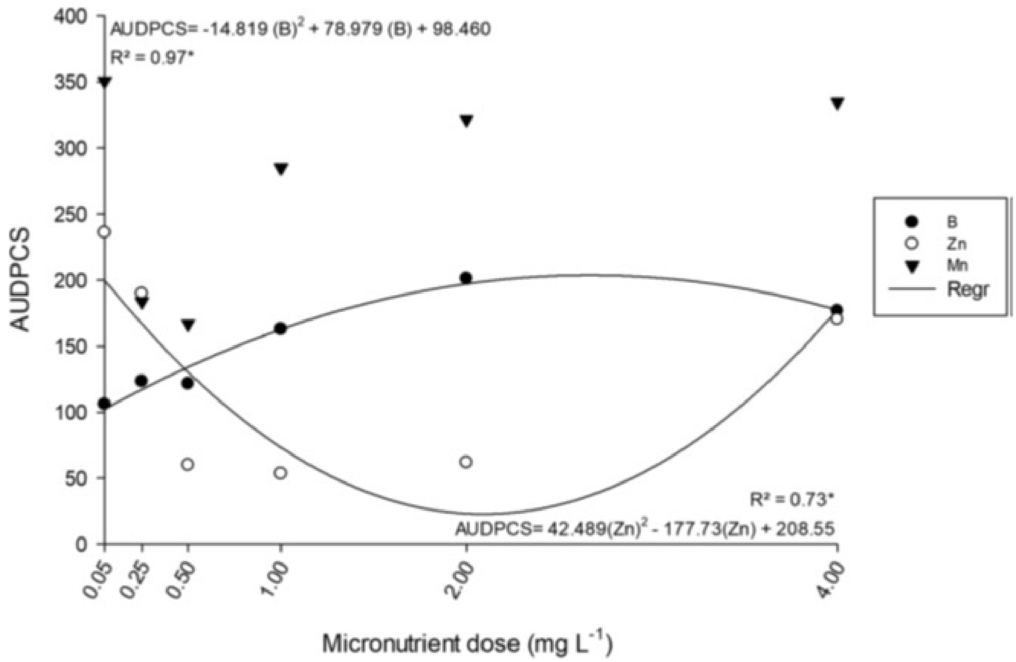

Figure 9: The relationship between area underseverity progress curve for (AUSPC) of coffee rust (*Hemileia vastatrix*) and dose of boron, zinc and manganese as applied to coffee seedlings grown in nutrient solution. (Pérez et al., 2020).

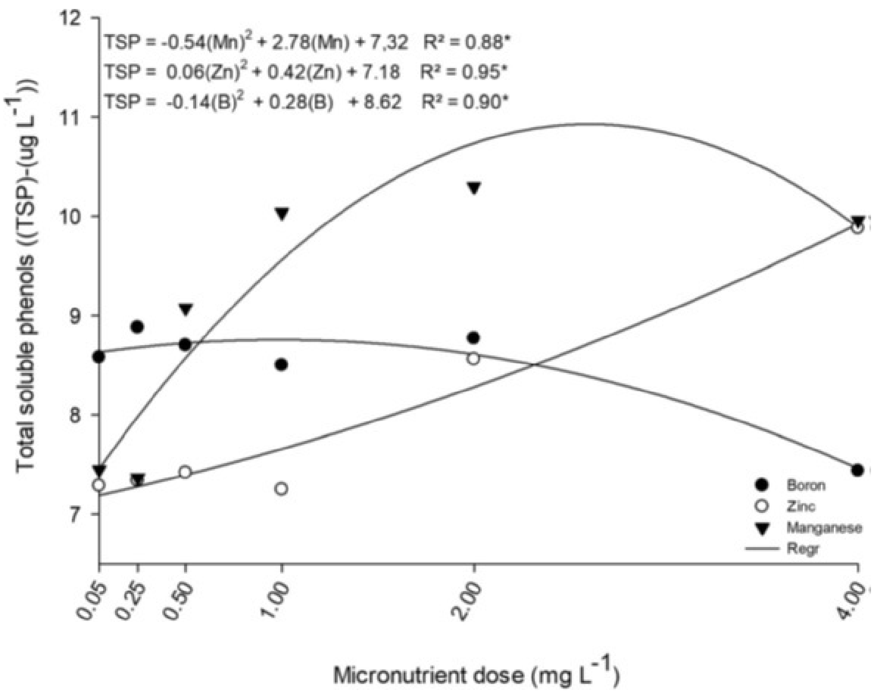

Figure 10: Relationship between total soluble phenols (TSP) in coffee leaves inoculated with *Hemileia vastatrix* and dose of boron, zinc or manganese applied to coffee seedlings grown in nutrient solution. (Pérez et al. 2020).

Various substrates were tested on seedlings in seedling plug pots in nurseries: S1 –commercial substrate I, S2 – commercial substrate II, S3 –substrate used for production of eucalyptus seedlings (30% carbonized rice hull, 10% subsoil earth, 40% cattle manure, and 20% vermiculite), and S4 –standard substrate consisting of 80% cattle manure + 20% subsoil earth. Tests were also performed on the effect of application of slow-release fertilizer at the dose of 10 kg of the formulation 15-10-10 + micronutrients, granulated and resin coated /m^{3}of substrate, or 1g per seedling plug, which were incorporated in the substrate. In general, the best substrates for formation of coffee seedlings in seedling plugs were the non-commercial or organic substrates (S3 and S4), regardless of having received supplemental fertilization or not. A relationship was observed between cercosporiosis and mineral nutrition, especially in regard to calcium. The plants of the substrate with greatest intensity of the disease had contents of around 8.7 g/kg of Ca in their shoots, which may have led to lower growth and development of the seedlings and greater intensity of the disease. In addition, substrates S3 and S4 had lower production costs (Pozza et al., 2007).

Adequate fertilization can increase disease resistance by contributing to the availability and limiting the imbalance of nutrients. The use of sustainable agricultural techniques, particularly organic agriculture, crop rotation, green manure crops, use of manure, and irrigation, made it possible to confirm the effect of crop management on disease resistance and on plant growth. Different organic sources of nutrients were tested by Santos et al. (2008) on management of rust in an organic coffee crop without irrigation. Coffee husk (2.4% K) combined with pig slurry (5.5% P) or castor bean cake (6.4% Ca) reduced disease incidence by 31% and 21%, respectively, compared to that observed in applying only coffee husk. More recently, the influence of different soil coverings, fertilizer types, and soil conditioners on the incidence and severity of brown eye spot (*C. coffeicola*) in coffee (*C. arabica*) during

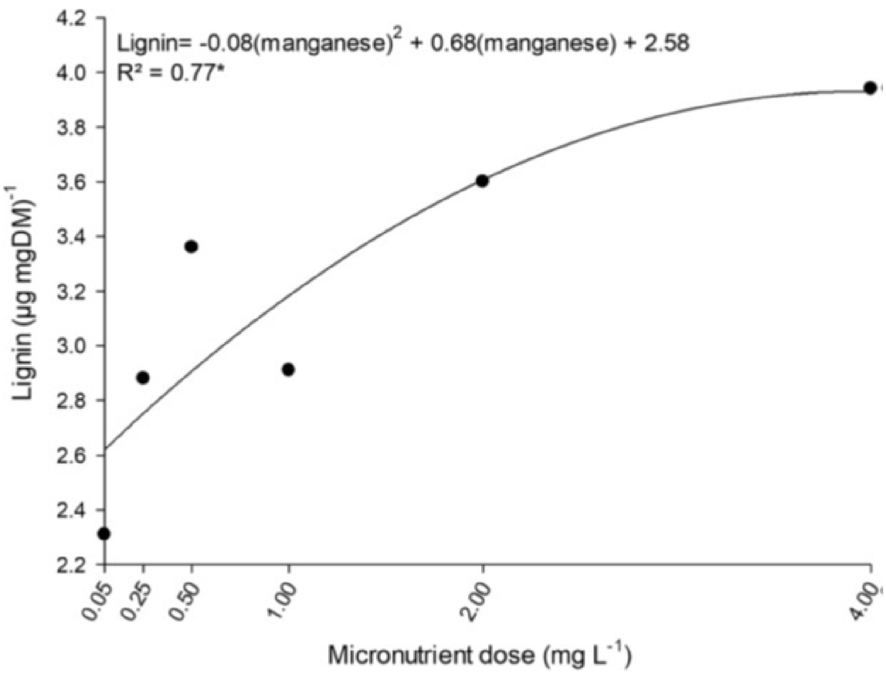

Figure 11: Relationship between concentration of lignin (µg mg DM^{-1} (dry mass)) in coffee leaves inoculated with *Hemileia vastatrix* and dose of boron, zincor manganese applied to coffee seedlings grown in nutrient solution. (Pérez et al., 2020).

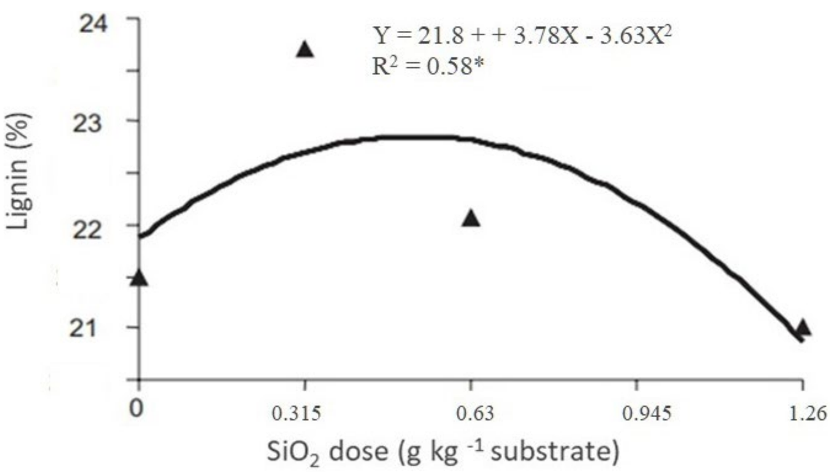

Figure 12: Lignin content in the leaf tissues of the coffee plant (*Coffea arabica*) according to silicon doses (g kg^{-1}substrate) (Santos Botelho et al., 2005).

the vegetative stage, were evaluated. The area under the progress curve for disease incidence and severity showed the lowest mean without soil covering, whereas that for number of leaves was greater with the use of the controlled-release fertilizer. The plastic film provided a greater soil moisture and a lower soil resistance penetration. The chemical composition of the organic compound reduced coffee plants growth. Soil covering with plastic film or *Urochloa decumbens* favors the high incidence of brown eye spot; however, it provides a greater soil moisture and, therefore, improves the growth of coffee plants in the vegetative stage (Resende et al., 2022a).

Different soil covers, fertilizers, and soil conditioners were also studied in management of cercosporiosis by Resende et al. (2022b). The plots were composed of soil covers including polyethylene film, *Urochloa decumbens,* and an area without cover. The split plots were treated with conventional fertilizers and controlled-release fertilizers. The split-split plots were composed of soil conditioners, including organic compost, coffee husk, agricultural gypsum, water-retaining polymer, and a control. *U. decumbens* and soil conditioners, including organic compost and coffee husk led to greater soil moisture, reducing cercosporiosis of leaves and fruit and, consequently, defoliation. In spite of the high soil moisture content present under the polyethylene film and later promotion of vegetative growth, this soil cover led to a greater incidence and severity of the disease on fruit and leaves and to greater defoliation. Though the controlled-release fertilizers did not lead to a significant reduction in disease incidence, they brought about improvements in vegetative growth and in leaf production. Agricultural gypsum increased yield, but caused nutritional imbalances and possible nutrient leaching, thus contributing to an increase in the occurrence of cercosporiosis, bringing about a reduction from 72% to 81% in the leaf area index of the coffee plant.

The use of sources of organic matter may have an effect on control of plant diseases (Ghini; Schoenmaker; Bettiol, 2002). However, the use of organic composts in control is associated with the pathosystem and with the type of organic compost used, such as the origin of the material to be composted, the composting method, the maturity stage of the compost, and the population composition of the decomposer microorganisms of the organic matter, among other factors (Hoitink; Fahy, 1986). The addition of green manure and animal manure resulted in suppressive soils in which the pathogens are not stabilized and do not affect the crop plants, as found by Ghini, Schoenmaker and Bettiol (2002). They determined that *Pythium* spp. was suppressed when they added chicken bedding to the soil.

Soil tillage can change the environment and these changes can result in an increase, reduction, or lack of effect on the incidence and severity of diseases, depending on the crop system and the disease. Minimum tillage of the soil concentrates crop residues on the soil surface and therefore also concentrates the number of propagules of the pathogen.

Management of irrigation and fertilization affected cercosporiosis in coffee fields under different management practices of drip irrigation and fertilization. Suspension of irrigation for 70 days from July to September 2012 favored the intensity of cercosporiosis, and in the same year, high application rates of NK increased yield (Barbosa Júnior et al., 2019).

5 NUTRIENT MANAGEMENT IN COFFEE DISEASES

The effect of soil fertility and of coffee plant nutrition on diseases intensity has been studied by various researchers, and they have observed their significance for disease control. These effects depend on various factors, such as type of soil, soil texture, structure, pH, amount of organic matter, soil water availability, and others. That is, they depend on the edaphic and climatic conditions of each region. Therefore, the effect of a nutrient on all diseases of all crops cannot be generalized. These are individualized studies, according to nutrient, crop, and pathogen. This will be shown below.

5.1 Rust (*Hemileia vastatrix*)

Some observations on coffee rust (CLR) in Brazil were recently reported by Sera et al. (2022). Most plantations are cultivated with susceptible cultivars, such as those from the Catuaí and Mundo Novo groups. Brazilian research institutes have developed dozens of cultivars with different levels of resistance and have significantly increased the planting of new resistant cultivars. The main sources of CLR resistance are genotypes of the Híbrido series from Timor, Icatu, BA, carriers of the SH3 gene and Ethiopian wild coffees. High CLR resistance is still observed in genotypes carrying Sarchimor and SH3. Intermediate CLR resistance is observed in Ethiopian wild coffees and in Sarchimor and Icatu derivatives, where qualitative resistance has been supplanted by races of *H. vastatrix*. Contact, mesostemic and systemic fungicides are used for chemical control in Brazil. The incidence of CLR in Brazil starts to increase after the beginning of the rainy season in November, reaches a peak in June and remains high until August. Thus, chemical control is normally applied from December to April.

Both lack and excess of N during the rainy summer can cause higher disease progress rates and increase rust intensity, especially close to harvest. The coffee rust progress in the field also had a negative correlation with leaf N content in plants of the cultivar Mundo Novo LCP-19 at eight years of age (Carvalho et al., 1996). The maintenance fertilization used was 160 g of N, 40 g of P_2O_5, and 160 g of K_2O per plant. A lower leaf N contents was observed in plants with higher percentages of the disease, passing from 47.89%to 55.39% of rust on plants with N content values from 30 g kg^{-1}

to 28.8 g kg^{-1}, respectively, showing the inverse correlation between these variables.

For potassium, the incidence and the defoliation brought about by rust of the coffee plant were greater with the use of organic fertilizers containing only coffee husk, whereas the lowest incidences and defoliation and the greatest yield occurred in the treatments with addition of castor bean cake and swine manure to the coffee husk. These treatments were more balanced in relation to the supply of Ca, Mg, and K (Santos et al., 2008). Another study also developed in the field by Custódio (2011) evaluated the effect of doses of potassium chloride (0, 100, 200, and 400 kg ha^{-1}) and of dolomitic limestone (0, 1, 2, and 4 t ha^{-1}) on rust progression. In that study a smaller area under the rust progress curve (5150.1) was observed at the medium limestone application rate (2 t ha^{-1}) together with the maximum potassium chloride application rate (400 kg ha^{-1}), reaffirming the need for balance among nutrients.

The combination of nitrogen and potassium fertilization affected the severity of rust in seedlings grown in nutrient solution. Pérez et al. (2019) found reduction in the disease with an increase in the N and K application rates, obtaining the lowest area under the severity progress curve at the combination of doses near 11 mmol L^{-1} of K and 23 mmol L^{-1} of N (Figure 13).

5.2 Phoma leaf spot (*Phoma tarda*)

The relation of N and K application on the intensity of phoma leaf spot in coffee seedlings was studied by Lima et al. (2010b). The treatments used consisted of 5 doses of N (3, 7, 11, 15, and 19 mmol L^{-1}) combined with 5 doses of K (4, 5, 6, 7, and 8 mmol L^{-1}). The increase in the doses of N and K in the nutrient solution significantly affected in an independent manner both the incidence and the severity of the disease. Thus, the increase in the doses of N showed an increase of 34.8% for incidence and 34.3% for severity (from the lowest to the highest dose), (Figure 14A). In relation to K doses, reduction in the intensity of the disease was observed with the increase in K up to a certain dose, after which the disease increased (Figure 14B). The lowest values of incidence and of severity were recorded at the doses of 6.59 mmol L^{-1}and 6.57 mmol L^{-1}of K, respectively.

The relation of Ca and K application on the disease intensity was also investigated. Catarino et al. (2016) tested increasing combined doses of Ca (2, 4, 6, 8, and 10 mmol L^{-1}) and of K (3, 4, 5, 6, and 7 mmol L^{-1}) and observed greater reduction in the area under the disease incidence progress curve of phoma leaf spot in the combination of the lowest dose of Ca with the highest doses of K (Figure 15A). In contrast, the area under the disease severity progress curve had the lowest value in the combination of the lowest doses of Ca and K (Figure 15B).

5.3 Brown eye spot or Cercosporiosis (*Cercospora coffeicola*)

In a greenhouse, Pozza et al. (2001) evaluated the effect of nutrition with N and K on the brown eye spot intensityon coffee seedlings in nutrient solution. The combinations of four doses of N (3, 7, 11, and 15 mmol L^{-1}) with four doses of K (3, 5, 7, and 9 mmol L^{-1}) were studied. The area under the progress curve of number of lesions per leaf decreased with the increase in the N doses, with the lowest value (269 cm^2) observed for the dose 11.69 mmol L^{-1} N combined with the lowest dose of K.

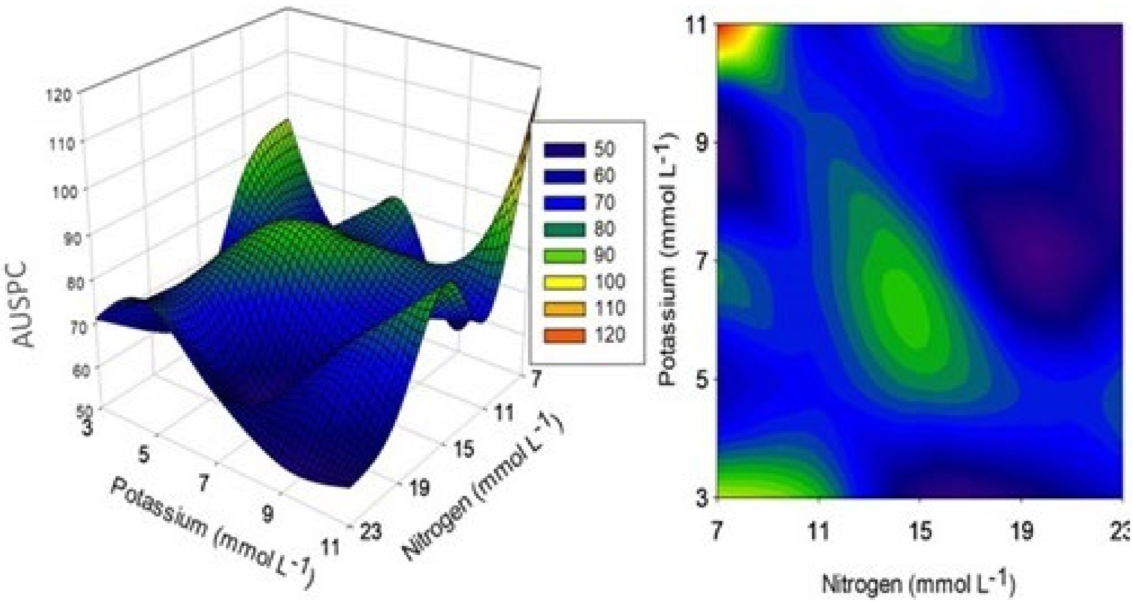

Figure 13: Area under the severity progress curve of rust (*Hemileia vastatrix*) in coffee (*Coffea arabica*) seedlings as a result of combined doses of nitrogen and potassium in nutrient solution (Pérez et al., 2019).

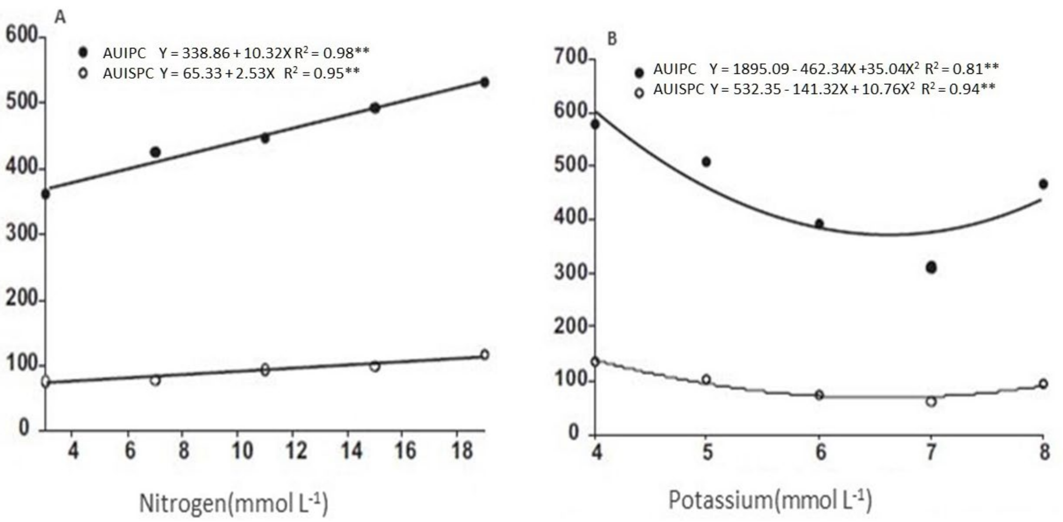

Figure 14: Area under the incidence progress curve (AUIPC) and area under the severity progress curve (AUSPC) of phoma leaf spot (*Phoma tarda*) in coffee (*Coffea arabica*) seedlings according to doses of nitrogen (A) and of potassium (B) in nutrient solution (Lima et al., 2010b).

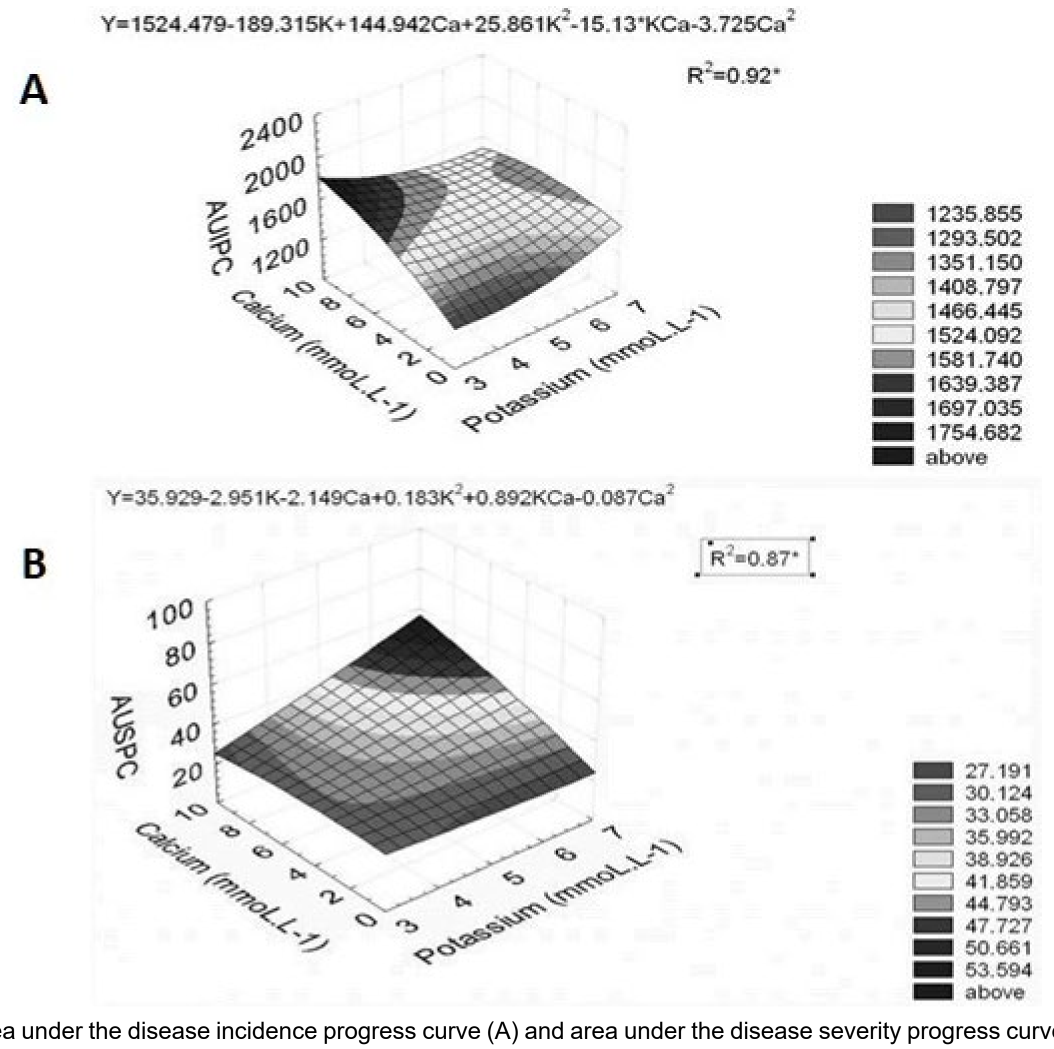

Figure 15: Area under the disease incidence progress curve (A) and area under the disease severity progress curve (B) of phoma leaf spot (*Phoma tarda*) in coffee (*Coffea arabica*) seedlings according to combined doses of calcium and potassium in nutrient solution (Catarino et al., 2016).

The effect of silicon on control of cercosporiosis in three varieties of coffee was studied by Pozza et al. (2004). Plants of the Catuaí variety treated with silicate showed a reduction of 63.2% in leaves with lesions and of 43% in the total number of lesions per plant. Microanalysis of X-rays (Figure 10) and the mapping for Si indicated uniform distribution of the element across the entire abaxial surface of the coffee leaves in the three varieties treated. In scanning electron microscope images, a well-developed wax layer was also observed on the lower surface of the leaves, which was thicker in Catuaí and rare or absent in untreated plants (Figure 16).

The cercosporiosis intensity in coffee seedlings according to sources and doses of silicon was also studied by Santos Botelho et al. (2005). The effect of calcium and sodium silicates was evaluated at the doses 0, 0.32, 0.64, and 1.26 g of SiO_2 kg^{-1} of substrate in seedlings of the Catuaí cultivar IAC 99.The smallest area under the progress curve of total number of lesions was obtained at the dose of 0.84 g kg^{-1} of sodium silicate. A linear decrease was observed for area under the progress curve of the number of diseased plants and an increase in leaf lignin concentration up to the dose of 0.52 g kg^{-1} of sodium silicate.

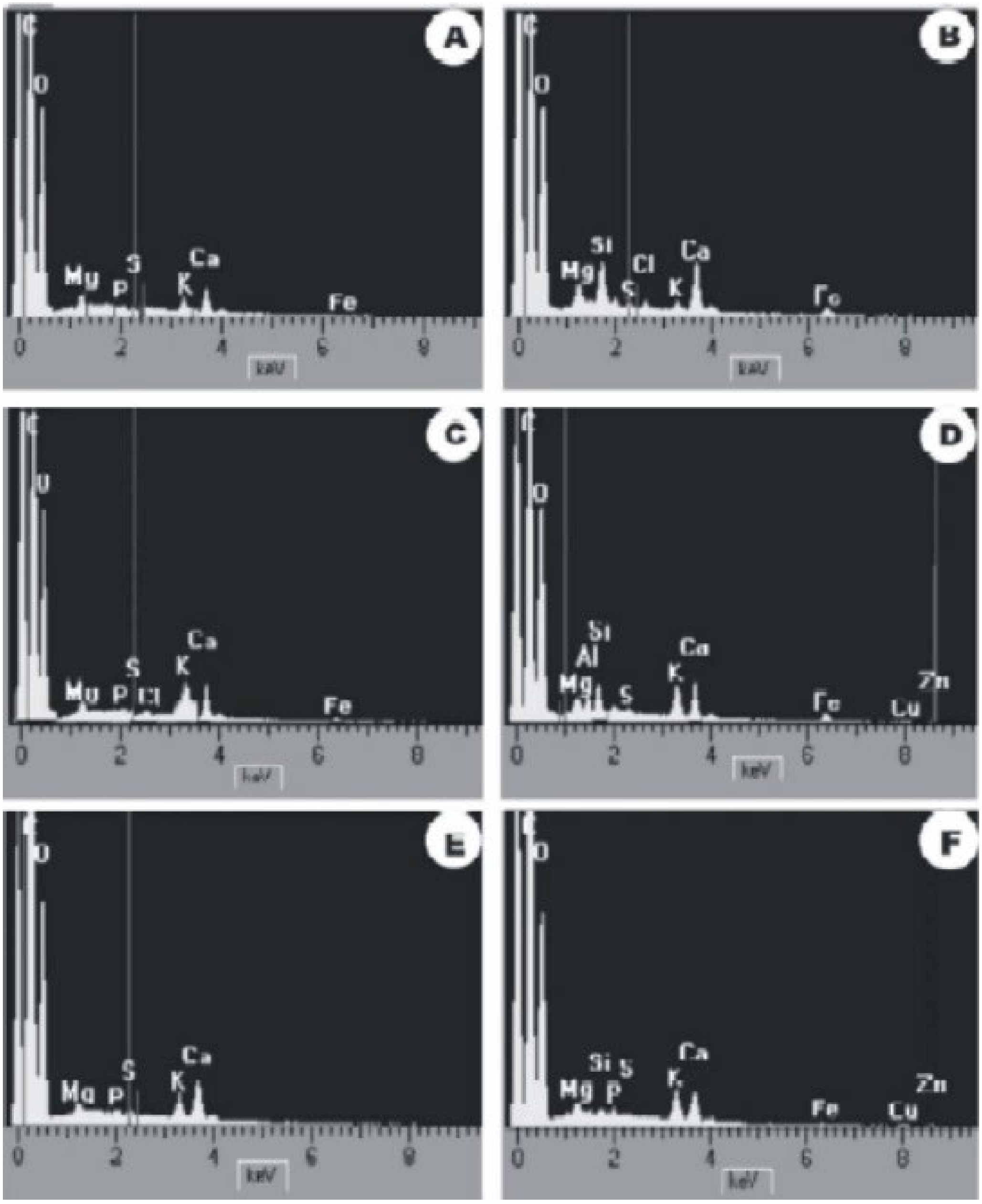

Figure 16: Microanalysis of X-rays of the lower surface of leaves of the following coffee (*Coffea arabica*) varieties (A-F): Catuaí (A-B), Mundo Novo (C-D), and Icatú (E-F). Microanalysis of untreated plant leaves (A, C, and E) and of leaves treated with $CaSiO_3$(B, D, and F) (Pozza et al., 2004).

Balanced plant nutrition improves coffee development and resistance to diseases such as cercosporiosis. In a study by Vilela et al. (2022) aimed to evaluate the effects of fertilization with nitrogen (N), phosphorus (P) and potassium (K), called NPK, on the incidence of cercosporiosis in rainfed coffee plantations in the vegetative phase, in a plantation of the cultivar Mundo Novo IAC 379/19. The fertilization levels used were 10, 40, 70, 100, 130 and 160% of the standard fertilization recommended for NPK. The incidence of cercosporiosis and the number of coffee leaves were evaluated from May to December 2019. Areas under incidence (AUIPC) and under progress curve the leaf number (AUPCNL) were estimated. Water potential and leaf chemical analysis were performed in April 2019, July 2019 and October 2019. The highest AUIPC was detected in plants with lower levels of fertilization. However, there was a reduction in the number of leaves due to the increase in the dose of NPK. The lowest leaf water potential occurred in July, when the disease was more intense. NPK fertilization levels influenced their concentrations in leaves, as well as other nutrients. The fertilization level of 100% favored the reduction of AUIPC, maintaining greater number of leaves and nutritional balance in coffee trees. NPK fertilization levels influenced their concentrations in leaves, as well as other nutrients.

In nutrient solution, Garcia Junior et al. (2003) studied the effect of different doses of potassium (1, 3, 5, and 7 mmol L^{-1}) and of calcium (2, 4, 6, and 8 mmol L^{-1}) on the incidence and on the severity of cercosporiosisin coffee seedlings of the cultivar Mundo Novo IAC 379-19. The areas under the progress curves of total number of leaves (AUPCNL), of incidence (AUIPC) and number of lesions (AUPCNL), just as the percentage of leaf area with lesions (LAL%),were significantly affected upon increasing the doses of K and upon combining the two nutrients. Thus, as for AUDIPC, a tendency of reduction in AUPCNL was observed as the doses of Ca increased, indicating the importance of this nutrient in constitution of the cell middle lamella. The reduction in AUIPC and AUPCNL with the increase in the doses of K up to 4.8 mmol L^{-1} is understandable, because according to Richardson and Croughan (1989), fungal toxins induce an increase in the efflux of K^+ ions, reducing the K content in the infected tissues and cells. From that dose on, there was competitive inhibition with other cations, because the high mobility of K in the plant favors this competition. The lowest LAL% (0.48%) was obtained with the doses of 7 mmol L^{-1} K and 6.2 mmol L^{-1} Ca. The lowest AUPCNL was also obtained with doses of K and of Ca similar to those obtained for LAL% (7 mmol L^{-1} K and 6.2 mmol L^{-1} Ca). The AUIPC according to doses of Ca also had a response similar to that found for LAL%.

Balanced nutrition of the plants improved the development of the coffee plant and resistance to cercosporiosis. With the aim of evaluating the effects of NPK fertilization on the cercosporiosis incidencein dryland coffee fields in the vegetative phase of the cultivar Mundo Novo IAC 379/19, Vilela et al. (2022) set up a field trial with levels of 10, 40, 70, 100, 130, and 160% of the standard fertilization recommended for NPK. Water potential and leaf chemistry were analyzed in April 2019, July 2019, and October 2019. The greatest area under the disease incidence progress curve (AUIPC) and under the progress curve of number of leaves (AUNLPC) was detected in plants with lower levels of fertilization. However, there was reduction in the number of leaves due to the increase in the dose of NPK. The lowest leaf water potential occurred in July, when there was greater intensity of the disease. The levels of NPK fertilization affected NPK concentrations in the leaves, just as of other nutrients. The 100% level of fertilization favored reduction in AUIPC, maintaining a larger number of leaves and nutritional balance in coffee plants.

The use of organic nutritional sources on cercosporiosis management was evaluated by Santos et al. (2008). The use of coffee husk (2.4% K) mixed with castor bean cake (6.4% Ca) reduced disease incidence by 38%. The greatest predisposition of the coffee plants to cercosporiosis was observed upon using only coffee husk, coinciding with higher leaf content of K and lower leaf content of Ca and Mg compared to the other sources of fertilization. This confirms once more the effect of imbalance of nutrients on increasing the intensity of diseases by bringing about variations in the biochemical and structural defense mechanisms of the host (Pratissoliet al., 2007).

Recently, the effect of five nanoparticles - NPs (Cu, Mn, Zn, Ag, and B) and the fungicide azoxystrobin + cyproconazole at five doses (3, 50, 100, 250, 500 mg L^{-1}), on the sporulation and mycelial growth rate (MGR) of *C. coffeicola* were quantified. The most effective in vitro dose (500 mg L^{-1}) was applied to coffee seedlings Mundo Novo 376/4 cultivar inoculated with *C. coffeicola*. The area under the disease progress curve (AUDPC), compound phenolic, lignin soluble and chlorophyll content were evaluated. The AgNP, CuNP, MnNP, ZnNP and fungicide reduced the germination of *C. coffeicola* spores. The addition of fungicide, BNP, CuNP, ZnNP and MnNP to the culture medium at the dose of 500 mg L^{-1} reduced the mycelial growth by approximately 100%, compared to the control. Lower AUDPC's were recorded for coffee seedlings sprayed with fungicide and AgNP (Carvalho et al., 2022).

5.4 Bacterial blight (*Pseudomonas syringae* pv *garcae*)

According to Huber and Haneklaus (2007), the correlation of nutrients with disease intensity was confirmed based on various events, including the effect of fertilization on the incidence and severity of specific diseases, as revealed in the above examples for rust, phoma leaf spot, and cercosporiosis of coffee. The second event cited by these same authors is in regard to comparison of the mineral concentrations in healthy or resistant plant tissues compared to diseased or susceptible tissues.

In the study of Belan et al. (2015) differences were found in distribution of mineral nutrients in coffee leaf tissues around lesions caused by different pathogens bringing about bacterial blight, phoma leaf spot, cercosporiosis, yellow rust, and bitter rot (Figure 17) through microanalysis of X-rays (MAX). Thirty-three chemical elements were detected in the leaf tissues; however, there was variation in the K and Ca content around the lesions of the different diseases. The highest K content was found in the asymptomatic tissues that surround the lesions, decreasing for the transition zone and reaching minimum content in the symptomatic tissues. In contrast, the highest Ca content was found in the symptomatic tissues, decreasing for the transition zone and reaching the minimum content in the asymptomatic tissues.

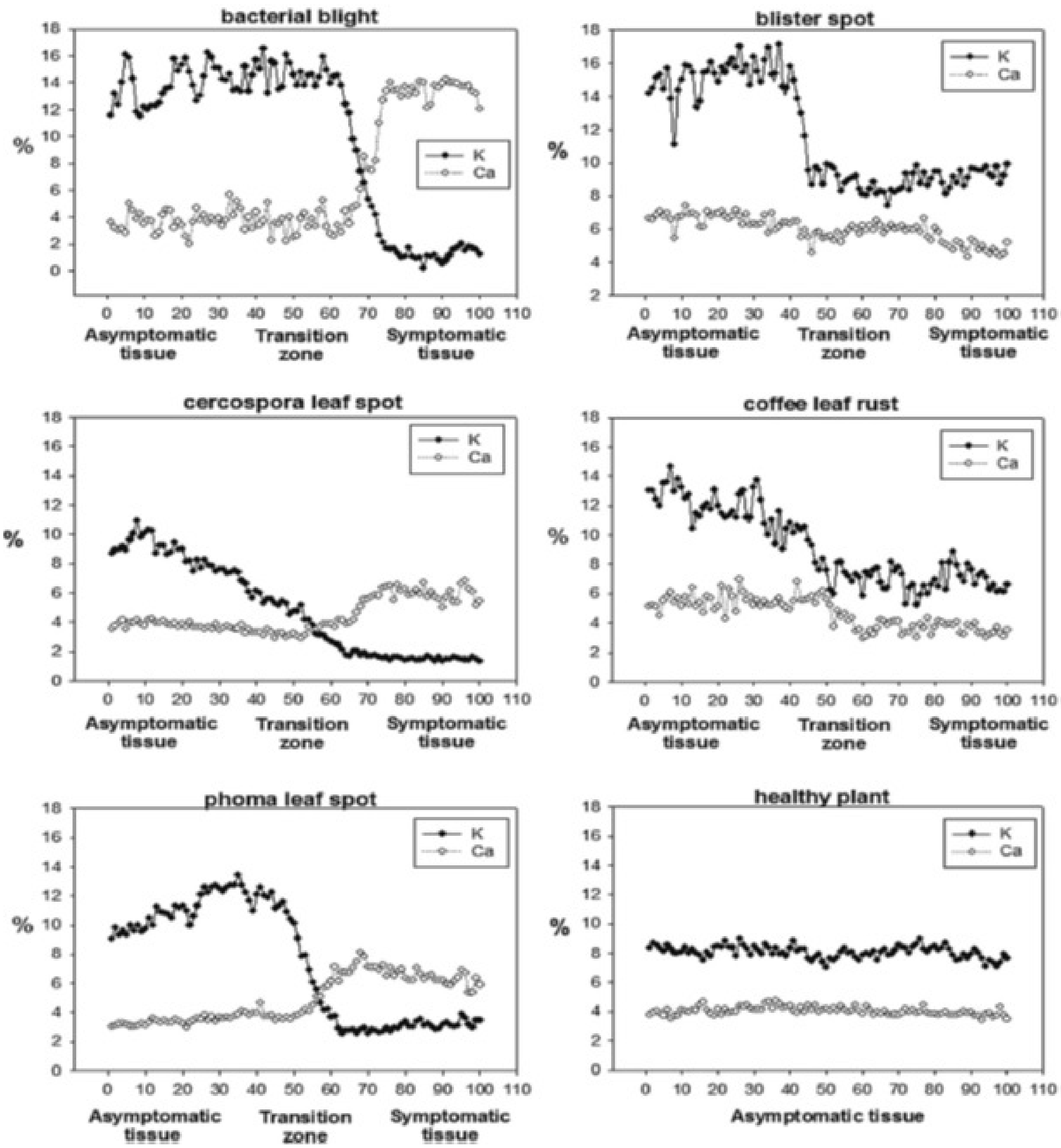

Figure 17: Distribution of the mineral nutrients potassium (K) and calcium (Ca) in asymptomatic and diseased coffee (*Coffea arabica*) leaves: bacterial blight (*Pseudomonas syringae* pv *garcae*), phoma leaf spot (*Phoma tarda*), cercosporiosis (*Cercospora coffeicola*), rust (*Hemileia vastatrix*), and bitter rot (*Colletotrichum gloesporioides*) (Belan et al., 2015).

Foliar sprays of 1% simple superphosphate were applied in the nursery, aiming to control bacterial leaf spot. In the manufacturing process of simple superphosphate there is generation of hydrofluoric acid (fluorine originating from natural phosphoric rock) and Mn. Thus, an experiment was carried out with these two elements in the control of this disease. The disease intensity was affected by combined doses of manganese and fluorine, as found by Velloso et al. (2021). The smaller area under the disease incidence progress curve and disease severity progress curve showed reduction with balanced application of these two nutrients. The effect of Mn and of F on photosynthesis of the coffee plant was also found. Doses between 0.7 and 1.4 g L^{-1} of Mn combined with doses of 0.10 to 0.12 g L^{-1} of F were more effective in suppressing the bacterialb light, after análisis for both variables. There was linear reduction in net photosynthesis as Mn increased. The metabolic changes caused by incorrect applications of Mn, for example, may have a direct effect on pathogens, including inhibition of growth, sporulation, replication, and production of enzymes and of toxins, or an indirect effect on the host (Marschner, 2012).

The most recent study involving the effect of nutrient management on the intensity of bacterial blight aimed to evaluate the effect of N and K application on control of the disease., Pérez et al. (2017) set up an experiment in a growth chamber, testing the combination of 5 doses of N (3, 7, 11, 15, and 19 mmol L^{-1}) with 5 doses of K (3, 5, 7, 9, and 11 mmol L^{-1}). No significant interaction of the two nutrients was observed on the intensity; only the N affected the disease. The smaller area under the disease severity progress curve (7.79) was obtained from the dose 13.34 mmol L^{-1} N. As of that point, there was a quadratic increase in the severity of the disease.

6 CONCLUSIONS

Mineral nutrients affect anatomical, biochemical, and physiological processes of plants, contributing to an increase in resistance to diseases when available at adequate concentrations in plant tissues. The study of management of nutrients in control of the main diseases of the coffee plant that occur in Brazil has led to improved understanding of the dynamics of mineral nutrition in the plant-pathogen complex.

In addition to the genetic potential of the cultivars, adequate nutrition should be exploited for complete genetic expression of resistance of the plants to diseases. Correct and balanced fertilization, together with efficient agricultural practices to make the nutrients of the soil solution available to plants, should continue to be studied. In sustainable agriculture, nutritional balance, just as water availability in the soil, is an essential component in some integrated crop protection programs by representing better cost/benefit. It is an ecologically viable measure for control of plant diseases upon reducing the number of applications of agricultural chemicals. The nutritional balance allows the coffee tree to express its best resistance potential to pathogens

7 AUTHORS' CONTRIBUTION

EAP wrote the manuscript and performed the experiment, AAAP supervised the experiment and co-work the manuscript, and EAP review and approved the final version of the work, AAAP conducted all statistical analyses.

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