How the Global Tea Industry Copes With Fungal Diseases - Challenges and Opportunities

Abhay K. Pandey,^{1,†} Ganga D. Sinniah,² Azariah Babu,¹ and Amarjyoti Tanti³

¹ Tea Research Association, North Bengal Regional R & D Center, Nagrakata 735225, West Bengal, India

² Tea Research Institute of Sri Lanka, Plant Pathology Division, St. Coombs, Talawakelle 22100, Sri Lanka

³ Tocklai Tea Research Institute, Tea Research Association, Jorhat 785008, Assam, India

Abstract

Tea (*Camellia sinensis* [L.] O. Kuntze) is a plantation crop, grown commercially in Asia, Africa, and South America. Among biotic threats to tea production, diseases caused by fungal pathogens are most significant. Worldwide, tea plants are challenged by several root, stem, and foliar diseases. Foliar diseases, blister blight, gray blight, and brown blight are particularly important as they adversely affect the bud and the two youngest leaves, causing loss of harvestable shoots. Over the past several decades, climate change and field management practices have influenced the risk of crop damage by several fungal pathogens, as well as the development and spread of diseases. Management interventions, such as the adoption of good cultural/agronomic practices, use of fungicides and microbial

biocontrol agents, plant defense elicitors, and deployment of resistant cultivars, have mitigated damage to tea plants caused by fungal diseases. A clearer understanding of knowledge gaps and the benefits of plant disease management strategies available is needed. The present article reviews the prevailing knowledge of major fungal pathogens of the tea crop, their genetic variability, the damage they cause and its economic impact, and the need for new disease management strategies as climate change intensifies. We will also emphasize important knowledge gaps that are priority targets for future research.

Keywords: tea plant, root rots, foliar diseases, management strategies, biological control

Tea (*Camellia sinensis* [L.] O. Kuntze) is a dicotyledonous perennial plant belonging to the family Theaceae. The tea plant grows up to 15 m tall under natural conditions but is maintained at waist height (1.0 to 1.5 m) in commercial plantations. Worldwide, more than three billion cups of tea are served each day. It is the most consumed drink other than water. Global tea production has had an annual growth rate of 4.4% over the last decade, and now exceeds six million tons per year (Anonymous 2019) with a projected increase to more than 8 million tons by 2027 (FAO 2018). Tea cultivation is a main source of livelihood in the major tea-producing countries. Worldwide, 13 million people are employed in tea production (Voora et al. 2019). Most tea is produced by smallholder farmers.

Cultivation of Tea as a Commercial Crop

According to a Chinese myth, tea was discovered by accident, around 2,732 BCE, by the Emperor Shen Nung, when a few tea leaves were blown into a kettle of boiling water and then used as

an herbal drink (Chang 1981). Tea cultivation began in Sichuan Province of China in the first century BCE (Chang 1981), and it was later introduced to Japan and other Asian countries. Currently, tea is extensively cultivated in more than 60 nations around the world (Fig. 1), predominantly in the tropics and subtropics (Hazra et al. 2019). Tea plantations cover 5 million ha of land area (FAO 2017). The tea crop has specific agro-climatic requirements, including temperatures in the 10 to 30°C range, minimum annual precipitation of 1,250 mm, acidic soils of pH 4.5 to 5.5, 0.5 to 10° slopes, and elevations up to 2,000 m above sea level. China, India, Kenya, Sri Lanka, Vietnam, Argentina, and Indonesia are the world's leading tea growing countries (Fig. 1). China is the major producer with 2.5 MT annually (FAO 2017), followed by India (1.3 MT), Kenya, and Sri Lanka. Collectively, these four countries contribute 86% of global tea production (Prathibhani et al. 2018). Tea is cultivated in a wide range of different types of terrain (Fig. 2A to D).

Commercial tea cultivars include *C. sinensis* var. *sinensis* (China-type small-leaf variety), *C. sinensis* var. *assamica* (Assam-type large-leaf variety), and *C. sinensis* var. *lasiocalyx* (Cambod-type). In tea manufacturing, freshly harvested green tea leaves and buds (Fig. 3) are transformed into dried leaves for brewing the tea. The major steps in tea processing are withering, rolling, fermentation (enzymatic oxidation), and drying. Tea has been categorized into three types depending on the fermentation process: non-fermented (green tea); partially fermented (oolong tea); and fermented (black tea).

The major biochemical constituents of tea include polyphenols comprising 20 to 50% flavonols (Yao et al. 2004), alkaloids (caffeine), amino acids, and vitamins that contribute to the quality (Engelhardt 2010), protection against biotic (Punyasiri et al. 2005) and abiotic

[†]Corresponding author: A. K. Pandey; abhaykumpandey.ku@gmail.com

The author(s) declare no conflict of interest.

Author Contributions: AKP, conceptualization and original draft preparation; GDS, guided during the draft preparation with significant inputs; AKP and GDS equally contributed to the manuscript; AB and AT, review and editing.

Accepted for publication 14 January 2021.

(Zeng et al. 2018) stresses, and that impart health benefits to the consumers. Health benefits of tea include prevention of cancer, diabetes, cardiovascular and neurodegenerative diseases, reduction of body weight, alleviation of metabolic syndrome (Yang et al. 2018), and

antiviral properties against influenza (Hayat et al. 2015) and severe acute respiratory syndrome (SARS) and other viruses (Chen et al. 2005), including the new SARS-CoV-2 (Mitsui et al. 2020; Sharma et al. 2020).

Fig. 1. Major and minor tea-growing countries of the world. The map shows both major tea-producing countries, which contribute to more than 90% of the global tea production, and the minor tea-producing countries, which supply the rest.

Fig. 2. Topography of the tea lands. **A**, Tea estate in Darjeeling, India. **B**, Tea estate in Sri Lanka. **C** and **D**, Tea harvesting.

Fungal Diseases of Tea Plants

Several pests and diseases interfere with the growth and performance of cultivated tea. Fungi are the main group of pathogens that cause diseases in tea plants. Tea plantations infected with fungal

Fig. 3. A harvestable shoot of a tea plant.

diseases may face losses in yield and quality. Fungal pathogens are associated with all parts of the tea plant, including foliage, stem, and roots. Generally, foliar diseases directly affect the harvest, while stem and root diseases influence the survival of tea plants. Blister blight, gray blight, brown blight, twig dieback, stem cankers, and root rots are considered the most impactful fungal diseases of tea plants worldwide.

Geographical Distribution, Economic Impact, and Epidemiology of Major Fungal Diseases of Tea Plants

Blister blight. The disease is caused by *Exobasidium vexans* Masee, an obligate, Exobasidiomycete pathogen. It is an economically important disease of tea plants that occurs in almost all tea-growing countries excluding those of Africa and the Americas (Arulpragasam et al. 1987; Barthakur 2011; Uddin et al. 2005). Blister blight was first reported in India in 1855 (Venkata 1979), and gradually spread to Japan in 1912, Vietnam in 1930, Ceylon (now Sri Lanka) in 1946 (Tubbs 1946), and Sumatra and Java (Indonesia) by 1959 (De Weille 1959). Tea is the only known host of the pathogen *E. vexans*. Extended periods of high humidity (<80%), moderate temperature (15 to 25°C), and long leaf wetness periods favor germination of basidiospores and disease development (De Weille 1959). Therefore, the disease is prevalent during wet and cool weather; these conditions occur most frequently where tea is grown at higher altitudes, such as the Darjeeling region of India (Barthakur 2011) and upcountry areas of Sri Lanka.

This fungus infects tea plants at both seedling and young stages in the nursery as well as at mature stages in the field, but only the succulent young leaves and stems are infected. The first foliar symptoms are lemon-green translucent spots on the first or second leaves of the harvestable shoots (Fig. 4A and B). Later, localized hypertrophy causes blisters on the lower surface, leaving a depression on the upper surface of a leaf. The basidiospores of this pathogen are produced on the tips of basidia on the exterior of the leaf, giving a powdery white coating to the blister on lower surfaces. Soon after the release of basidiospores, blisters start to become necrotic from the center. Stem infections cause extensive shoot dieback, which delays the recovery of pruned tea bushes (Balasuriya 2008). The survival of this obligate biotroph during unfavorable weather is still unclear; however, Ajay et al. (2009) suggested that it survives as thick-walled basidiospores. Polycyclic infections under the favorable environmental conditions resulted in 20 to 50% yield losses in Sri Lanka (Arulpragasam et al. 1987), Indonesia (Gulati et al. 1993), and India

Fig. 4. Symptoms of blister blight on A, adaxial and B, abaxial surfaces of tea leaves.

(Radhakrishnan and Baby 2004). In addition, blister blight also affects quality of processed tea by influencing caffeine production (Murr et al. 2015) and lowering catechins, amino acids, and aroma compounds (Gulati et al. 1993; Ponmurugan et al. 2016).

Brown blight/anthracnose. The disease is prevalent in Bangladesh, China, Hawaii, Japan, India, Indonesia, and Sri Lanka. In Japan and China, brown blight, also called anthracnose, is the most widespread disease (Wang et al. 2016; Yoshida et al. 2010). However, in other countries, it causes minor infection to tea plants. Anthracnose is caused by several species of the genus *Colletotrichum*. While *C. camelliae* has been recorded in China, Sri Lanka, and the U.S.A. (Liu et al. 2016; Orrock et al. 2020; Wang et al. 2016), *C. theae-sinensis* was found in Japan (Yoshida and Takeda 2006), and *C. gloeosporioides* (Guo et al. 2014) and *C. acutatum* (Chen et al. 2017) in China. Species of *Colletotrichum* have broad host ranges, causing anthracnose in a variety of crops including cereals, legumes, fruits, vegetables, and several perennial crops (Pandey et al. 2018). The scale of damage to the yield and the economic losses are not well understood for the tea crop, but recent studies revealed that it was causing significant losses to the harvestable shoots (Chen et al. 2017).

Symptoms on the leaves appear as small, yellowish green, diffuse spots that later become dark brown, necrotic lesions with characteristic concentric rings. These spots develop from the leaf margin and spread inward (Fig. 5A and B). Later, black fruiting bodies develop in the lesions, and the spots can coalesce, blighting young leaves and causing twig dieback. The pathogens survive in decomposed plant debris, and disease development is favored by high humidity (>95%), and temperatures of 25 to 30°C as well as by poor air circulation or prolonged periods of leaf wetness (Liu et al. 2016).

Gray blight. *Pestalotiopsis longiseta* (Speg.) K. Dai & Tak. Kobay and *P. theae* (Sawada) Steyaert cause gray blight in tea plants worldwide (Barthakur 2011; Maharachchikumbura et al. 2013). These necrotrophs belong to class Sordariomycetes. Gray blight is prevalent in China, Korea, Kenya, Japan, India, and Sri Lanka (Chen et al. 2018; Park et al. 1996; Takeda 2002); severe infections have been reported in Japan (Takeda 2002), Kenya, and India (Joshi et al.

2009). Yield loss in severely affected tea plantations was estimated at 10 to 20% in Japan (Horikawa 1986; Keith et al. 2006) and India (Joshi et al. 2009).

Gray blight symptoms first appear as brown concentric spots in the middle of the leaf, which later turn gray with brown margins and spread throughout whole leaf, causing damage to young developing shoots. Minute acervuli can be seen in the center of lesions (Fig. 6A and B). Both young and mature leaves are attacked by *Pestalotiopsis* spp., but infection of young shoots results in dieback. Mechanical damage to plants by farming equipment aids initiation and development of the disease (Joshi et al. 2009). The pathogen survives in infected crop debris and in soil for many years. Environmental conditions, temperatures around 35°C, and relative humidity >85% favor disease development.

Cankers and twig dieback. Cankers occur in all tea-growing countries (Ponmurugan and Baby 2007). The most prevalent type is collar canker, also known as Phomopsis canker, which targets the main stem and is caused by the sordariomycete parasitic fungus *Phomopsis theae* Petch. Stem and branch canker, also known as Macrophoma canker, is also an important disease of tea plants, and is caused by the Dothideomycete *Macrophoma theiocola* Siemaszko. In recent years, Botryosphaeriaceae fungi (*Lasiodiplodia theobromae*, *Botryosphaeria dothidea*, and *B. mamane*) have been reported as the primary canker-causing pathogens in tea plantations of Sri Lanka (Liyanage et al. 2016). Collar canker has been reported from India, China, Kenya, Japan, Bangladesh, and Sri Lanka (Ahmad et al. 2016; Balasuriya 2008; Keith et al. 2006), whereas stem and branch cankers have been reported from Sri Lanka, India, and Bangladesh (Ahmad et al. 2016; Barthakur 2011; Sinniah 2018). Phomopsis canker attacks stem and twigs, kills branches, and, after moving downward in the plant, causes decay of the entire bush. A yield loss of 40 to 50% was reported due to twig dieback caused by *Fusarium solani* (Mart.) Sacc (Fig. 7A and B) in Taiwan (Muraleedharan and Chen 1997), and collar and branch cankers in central Africa (Rattan and Sobrak 1976). Phomopsis canker can cause the death of 2- to 8-year-old bushes, significantly reducing establishment of tea plantations (Balasuriya 2008).

Fig. 5. Symptoms of brown blight on A, adaxial and B, abaxial surfaces of tea leaves.

The fungi that cause stem and branch cankers enter the stems, kill the bark, and produce small, red, elongated droplets of exudates, followed by typical canker symptoms (slightly sunken lesions surrounded by a ring of callus growth) (Fig. 8A). However, cankers caused by *P. theae* are usually found on the collar regions and at the base of branches and twigs, associated with wounds caused by mechanical damage. In general, infected bushes show brown or yellow leaves and cankers or lesions on the collar regions. The canker pathogens enter the plant through wounds and initiate infection. The fungal pathogens are transmitted by windborne spores, which survive for several weeks on pruned branches left in the field, and spread through rain splash across the surrounding areas. After infection occurs, dry atmospheric conditions and pruning operations promote canker development (Barthakur 2011). Recently, canker pathogens belonging to the *F. solani* species complex were reported in Sri Lanka (Fig. 8B). Discoloration of wood, the presence of salmon pink perithecia in the collar regions, and rapid dieback of infected bushes differentiate Fusarium canker from Phomopsis canker (Sinniah et al. 2017).

Root rots. The fungi *Poria hypolateritia* Berk. ex Cooke (*Ceriporiopsis hypolateritia* [Berk. ex Cooke] Ryvarden), *Phellinus noxius* (Corner) G. Cunn., *Armillaria mellea* (Vahl) P. Kumm., and

ordariomycete *Rosellinia arcuata* Petch., *R. bunoides* (Berk. and Br.) Sacc., *Ustulina zonata* (Lév.) Sacc., Sylloge., and *U. deusta* (Hoffm.) Maire are the major root rotting pathogens in tea plants. Red root rot caused by *P. hypolateritia* in India, Indonesia, and Sri Lanka (Balasuriya 2008; Chong and Fazila 2012), and Armillaria root rot in African countries, are of economic concern.

P. hypolateritia is a necrotrophic, soil-borne fungus that attacks both young and old tea bushes (Fig. 9A), and spreads through windborne spores or through the soil by freely growing, threadlike white rhizomorphs (Fig. 9B). These rhizomorphs appear on the root surface at an early stage of the infection, which later turn red and form a network over the root surface. During the progression of the disease, infected roots show red and white spots that later disintegrate into a soft pulp (Fig. 9C). The pathogen survives in the soil and infects roots during humid and rainy seasons (Chong and Fazila 2012). The percent yield loss has not been worked out for red root rot; in India, however, Barthakur (2011) noticed that once this pathogen infects tea bushes, it spreads throughout the surrounding areas and causes significant loss.

In Kenya, about 50% yield loss has been recorded in smallholder plantations due to Armillaria root rot (Onsando et al. 1997). Longitudinal cracks on the root and collar regions, and sheets of creamy

Fig. 6. Symptoms of gray blight on tea leaves in A, initial and B, advanced stages.

Fig. 7. A and B, Symptoms of twig dieback of tea plants.

white, fan-shaped mycelia under the bark are the characteristic symptoms. The leaves of infected tea bushes become chlorotic and wilt, and defoliation leads to death of the bushes.

Monitoring Diseases and Diagnostics

Traditionally, disease surveillance and monitoring practices involve the reporting of diseases by workers, field staff, managers, or

extension staff from the tea plantations followed by laboratory investigations. Disease monitoring often involves continuous, systematic collection, analysis, and interpretation of disease outbreaks and related factors, and use of the findings in devising the disease management practices. Properly designed field monitoring systems and tools, such as statistics, risk mapping, GIS, and remote sensing are lacking in the global tea industry. However, weather-based disease forecasting models have been developed for blister blight in Sri

Fig. 8. Symptoms of cankers of tea plants. A, *Macrophoma* canker; B, *Fusarium* canker.

Fig. 9. Symptoms of red root rot. A, Aboveground symptoms of a tea bush. B, Root showing whitish rhizomorphs at the early stage. C, Reddish rhizomorphs at the later stages.

Lanka (Kerr and de Silva 1969), India (Premkumar et al. 2002), and Indonesia (Gunadi 2001). These models are limited to research and their field level application in routine disease management is minimal. Recently, attempts were made to develop remote sensing techniques for monitoring tea plantations (Zhu et al. 2019) and remote detection of blister blight (Edwin et al. 2018; Peiris et al. 2019). These preliminary studies showed the possibilities of using advanced surveillance tools such as remote sensing and GIS technology in disease monitoring and management. These technologies may have more acceptability in the future, as tea is grown as a monoculture crop, covering larger areas, so that the use of human resources can be minimized.

Reliable detection and identification of pathogens is critical for formulating effective management strategies. In recent years, in addition to conventional methods, DNA sequence analysis has been used for the identification of pathogens causing gray blight (Chen et al. 2018; Maharachchikumbura et al. 2013), blister blight (Mohktar and Nagao 2019), brown blight (Chen et al. 2017; Orrock et al. 2020), and cankers (Liyanage et al. 2016; Mareeswaran et al. 2018; Sinniah et al. 2017).

In addition, random amplification of polymorphic DNA (RAPD), inter simple sequence repeat (ISSR), and simple sequence repeat (SSR) molecular markers have been used for the study of genetic variability among different isolates of fungal pathogens causing brown blight (Guo et al. 2014; Rabha et al. 2016) and gray blight (Joshi et al. 2009). This molecular information will be useful for the accurate identification of fungal pathogens or pathogen populations in tea plants. Nevertheless, the use of advanced molecular techniques in disease diagnosis, population studies, and host-pathogen interaction is still in its infancy compared with other commercial crops (Gilbert et al. 2008). Whole genome sequence information is not yet available for the fungal pathogens infecting tea plants. This evidence on the genetic makeup and advanced molecular studies will be helpful in understanding the population genetics of fungal pathogens, which will be further useful in selection for resistance among tea varieties against the diseases.

Impacts of Climatic Factors on the Fungal Diseases

Tea production is geographically limited to a few areas around the world due to its specific agro-climatic requirements. The reports of the working group on climate change of the FAO intergovernmental group on tea highlights that all the major tea-producing countries are facing rising temperatures and extreme weather events, such as drought, torrential rains, and violent windstorms, resulting in declining yields (FAO 2016).

Increase in temperature of the earth due to global warming may change disease risks in tea production (Muoki et al. 2020). Fusarium shoot (*F. solani*), which was considered a disease of minor importance in India, is becoming a major threat to the tea plantations of northeast India due to an increase in temperature, and may cause future outbreaks across the country (Kumhar and Babu 2019). The extensive use of machines for harvesting tea shoots, coupled with high temperature, caused higher incidence of bird's eye spot (*Cercospora theae* Petch) and gray blight in southern Indian tea estates; previously, these diseases were considered minor in importance (Ajay et al. 2009; Baby 2001; Gnanamangai and Ponnurugan 2012; Sanjay et al. 2003).

Climate change-driven disease spread has also been observed in blister blight. Blister blight, which traditionally occurred in China only in the tropical Yunnan and Hainan provinces, has become a problem in subtropical zones such as the Songyang and Pujian regions of Zhejiang Province, possibly due to increased atmospheric temperature and relative humidity (Han et al. 2018). Blister blight has become more prevalent during the rainy season in the tea plantations of northeast India (Bhujel et al. 2016) and South India (Ponnurugan et al. 2019). Such occurrences may be influenced by climate change. Climate change affects not only the pathogen, but also tends to cause biochemical changes in the host that influence host-pathogen interactions. The increase or decrease of temperature, water stress, and CO₂ causes alteration in several defense-related enzymes (Wang et al. 2011). Tea plants grown at higher

temperatures showed lower levels of caffeine and catechin (Lee et al. 2010; Wang et al. 2011), which play a major role in defense against blister blight, gray blight, and anthracnose (Langat et al. 1998; Li et al. 2016; Sinniah et al. 2014). In another study, Cheruiyot et al. (2008) have shown a reduction in the content of epicatechin and epigallocatechin when tea plants were subjected to water stress.

The impact of rising atmospheric CO₂ level on the incidence of tea diseases is evident in China. The severity of anthracnose increased significantly due to elevated CO₂, which reduced the caffeine content of tea leaves (Li et al. 2016). Similarly, a decrease in caffeine content after CO₂ enrichment was reported from Kenya, but an increase in catechin content in tea plants was also noticed (Li et al. 2017). These findings suggest that increases in temperature, CO₂, or water stress due to global warming results in biochemical changes in tea plants that may alter host-pathogen interactions. Future research needs to be focused on how major diseases in tea would react to predicted climate changes.

Current Disease Management Strategies

Tea, as a perennial crop under the monoculture system, stands in the environment for years and experiences numerous agronomic practices throughout its lifespan. The tea plant encounters many seasonal (blister blight, gray blight, and brown blight) as well as perennial diseases (canker and wood rots) during its lifespan. In annual crops, diseases are managed by tillage, rotation, and delayed seeding/sowing that disrupt the disease cycle. However, such practices are not feasible for the perennial tea system. The occurrence of disease, extent of damage caused, and the strategies adopted for disease management are generally specific for each tea-growing country. Integrated disease management (IDM), including the use of cultural, chemical, and biological methods and host plant resistance, practiced in the global tea industry, is discussed here.

Cultural practices. Basic management practices focus on two main approaches: (i) avoiding the introduction of pathogens into areas where the disease is not present, and (ii) lowering the disease severity. Grasses (nonhost plants) "Mana" (*Symbopogon confertiflorus* Steud.) or Guatemala grass (*Tripsacum laxum* Nash) are grown for 18 to 24 months prior to tea planting in Sri Lanka and India in order to protect tea plants from root rot diseases (Balasuriya 2003). In India, shade trees are an integral part of the tea plantations, as higher temperatures detrimentally affect the yield of tea bushes (Barthakur 2011). Conversely, higher humidity under shade trees favors foliar fungal diseases. Shade thinning at the onset of disease season, and "skiffing" of the infected tea shoots (removal of shoots at a height of 2 to 3 inches from the harvesting/plucking table, Fig. 2C and D) have been practiced to reduce the blister blight in some Asian countries (Balasuriya 2008; Barthakur 2011). In addition, frequent harvesting of shoots including "fish-leaves" (oval-shaped leaves that arise below the lowest normal flush leaf in a growing shoot), followed by removal of symptomatic leaves from plantations before the fungus starts sporulating on them, help keep blister blight at lower levels (Balasuriya 2003). Pruning below the point of infection (sanitary pruning) has also been practiced for the management of blights, cankers, and wood rot diseases (Ahmad et al. 2016; Uddin et al. 2005).

Host plant resistance. Conventionally, disease-resistant cultivars identified either by selection (based on experience) or evaluations have been promoted in the tea industry (Gunasekare and Kumara 2005). However, published information is limited. Tea varieties, such as Indonesian, Roupie, and Qi Men, were reported as resistant to gray blight in Pakistan (Akbar et al. 2017), and some newly developed tea cultivars were recorded as resistant to blister blight from India (Baby 2006) and Sri Lanka (Sinniah et al. 2016). In recent years, PCR-based molecular markers have proved a useful technique, enabling the introgression of resistant genes into breeding materials (Jayaswall et al. 2016). There is a noteworthy contribution on developing RAPD and sequence characterized amplified region (SCAR) molecular markers against blister blight (Karunarathna et al. 2013, 2020); these markers are useful for potential early detection of resistant and susceptible varieties of tea against blister blight.

A number of resistance genes in tea plants have been identified against blister blight (Bhorali et al. 2012) and anthracnose (Wang et al. 2016). Jayaswall et al. (2016) reported that the expression pattern of R gene (RPM1), defense enzymes (SOD, MPKK6), transporters (MDR), retrotransposons (LTR), and transcription factors (WRKY, NPR) were associated with resistance against blister blight; however, their functional relationship to blister blight resistance awaits clarification. Two independent, dominant resistance genes, *PI1* and *PI2*, have been reported to be involved in resistance to gray blight (Takeda 2002).

The presence of higher levels of naturally occurring polyphenols (epicatechin and catechin) in tea plants was attributed to their resistance against blister blight (Chakraborty et al. 2005; Sinniah et al. 2014) and gray blight (Langat et al. 1998). Similarly, the greater expression of pathogenesis-related proteins, PAL (phenylalanine ammonia lyase), β -1,3 glucanase, and chitinase was shown to be related to the resistance of tea plants against gray blight (Senthilkumar et al. 2019). In contrast, increased sugar level and antioxidant enzymes were associated with higher susceptibility of tea plants to collar canker (Ponmurugan and Baby 2007) and gray blight (Palanisamy and Mandal 2014), respectively.

Chemical fungicides. Fungicides have shown effectiveness in controlling major diseases of tea plants. However, some effective fungicides are not allowed to be used in tea because of concerns about residue levels in processed tea, and their possible adverse effects on the environment and workers (Dixon 2014). The major groups of fungicides that have been frequently used against various diseases of tea are demethylation inhibitors (DMIs) and methyl benzimidazole carbamate (MBC). Carbendazim and thiophanate methyl (MBC: FRAC code 1) have been used for controlling gray blight (Pallavi et al. 2012; Sanjay et al. 2008), while hexaconazole (DMI: FRAC code 3) is used to manage blister blight (Ajay and Baby 2010) in India. Soil drenching with 2% carbendazim has been found to reduce Phomopsis canker (Ponmurugan and Baby 2007). Nano-copper, carbendazim, and DMI fungicides are used against root rots (Balasuriya 2003; Ponmurugan et al. 2016). However, root infections in tea are not curable when they are diagnosed at advanced stages. In addition, inorganic copper-based fungicides (cuprous oxide, copper hydroxide, copper oxychloride, FRAC code M01) and amines (Calixin, FRAC code 5) have been used to manage blister blight (Arulpragasam et al. 1987; Thakur and Masand 2015).

Development of fungicide resistance in pathogens has been reported in tea. For instance, gray blight pathogens have become insensitive to continuous use of benzimidazole (Omatsu et al. 2012; Oniki et al. 1986) and strobilurin (Omatsu et al. 2012; Yamada et al. 2016). *Macrophoma theicola* has shown insensitivity to hexaconazole (Liyanaage et al. 2013). Therefore, application of fungicide resistance management strategies, such as rotation of fungicides with different modes of action, tank-mixing of selective and broad-spectrum fungicides, and integrating fungicide spray programs together with other disease management practices, should be executed at the provincial and nationwide level, as recommended by the Fungicide Resistance Action Committee (FRAC). Judicious application of newer fungicide active ingredients that are ecologically safe and efficient at lower doses would also be helpful in managing fungicide resistance in pathogens of tea plants (Sierotzki and Scalliet 2013).

Biological control. Several potential bacterial (*Bacillus* spp. and *Pseudomonas* spp.) and fungal (*Trichoderma* spp.) antagonists have been identified as microbial biological control agents (MBCAs) against fungal pathogens of tea plants. However, most of these MBCAs were screened in vitro (Kabir et al. 2016; Mareeswaran et al. 2018) without subsequent field trials. A few MBCAs have been evaluated at the field against blister blight (Rayati 2011; Sarmah et al. 2005) and gray blight (Phong et al. 2014). The use of microbial consortia has been found to be more effective than the use of a single antagonist (Elango et al. 2015; Nepolean et al. 2015). Researchers have found that the degree of biocontrol activity of MBCAs of the same species may differ under different environmental conditions. The variations in effectiveness can be related to differences in isolates/strains of MBCAs, types of formulations, types of carriers in the formulation, and method and time of application (Premkumar et al. 2009). In addition to MBCAs, leaf extracts of *Datura metel*

and *Azadirachta indica* (Saha et al. 2005), as well as *Xanthium strumarium* (Ramashish 2015), have shown effectiveness in controlling gray blight and blister blight, respectively, under field conditions.

Role of defense elicitors in disease management. The application of microbial inoculants and chemical elicitors have shown increase in levels of defense enzymes (PAL, peroxidase, chitinase, nitric oxide, and β -1,3-glucanase) in tea plants either through induced systemic resistance (ISR) or systemic acquired resistance (SAR) mechanisms, which enhanced resistance against several diseases (Walters et al. 2009). Elicitors that can induce SAR, namely salicylic acid, acibenzolar-S-methyl, and chitosan, have been used for managing blister blight (Ajay and Baby 2010; Chandra et al. 2017). Probenazole, prohydrojasmon, and tiadinil have been tested against gray blight and anthracnose (Yoshida et al. 2010). Treatment of salicylic acid combined with copper hydroxide showed higher efficiency in controlling blister blight than the application of salicylic acid alone (Sinniah et al. 2014).

The microbial defense elicitors, plant growth promoting rhizobacteria (PGPR) strains (*Bacillus* spp. and *Pseudomonas* sp.), and arbuscular mycorrhizal fungi (AMF) have been used to manage red root rot (Chakraborty et al. 2016) and blister blight (Saravanakumar et al. 2007). The microbial elicitors suppressed the activity of cellulose and pectin enzymes produced by the pathogens and enhanced the activity of defensive enzymes through ISR (Saravanakumar et al. 2007). Since these elicitors do not have any negative impact on the growth and chemical composition of harvestable shoots (Saravanakumar et al. 2007), they can be exploited for disease management in tea plantations. However, their compatibility with other components of IDM needs to be worked out.

Challenges and Prospects in Disease Management

Producing a good quality tea, free of pesticide residues, at an affordable cost, while ensuring social and environmental sustainability under changing climate is the current challenge faced by the global tea industry. Harsh weather events (intense rainfall, frequent drought spells, hail, and frost) are becoming more frequent in tea-growing countries in the global climate change scenario (FAO 2016). The changes in rainfall pattern and intensity in tea-growing countries interfere with the timing of agronomic practices, such as plucking, pruning, agricultural inputs, and the adoption of IDM. As discussed above, the changes in climate have influenced disease emergence and spread. The climate change-induced changes in China were estimated to increase the cost of pest and disease management to US\$78.69/ha (FAO 2016). As tea production is controlled by genotype, environment, and management, implications of climate change are felt at the regional as well as the country level. Therefore, it is necessary to focus on the location-specific IDM practices considering the site requirements in order to address the issues of a country and the global tea industry as a whole.

The compliance with a maximum residue limit (MRL) set for the pesticides as a food safety standard is a major challenge in tea export. The competitiveness of tea in export markets is challenged by strict regulations on MRLs. The European Union (EU) has increased the number of pesticides regulated for tea over the years to 457 pesticides (Regulation EU 396/2005/EC current version 2019/1243). At present, different countries established MRLs for tea to reflect their needs, conditions, and capabilities. Thus, MRL regulations vary across countries, and there is no international agreement on the harmonization of regulations (FAO 2015). For example, MRL established for the fungicide propiconazole is 0.05 mg/kg, 4 mg/kg, and 0.01 mg/kg by the EU, U.S.A., and Japan, respectively (FAO 2015).

Further, MRLs for tea are regulated based on the pesticide residues found on dried leaves, although tea is consumed as a brewed beverage (FAO 2014). This situation greatly influences the choice of fungicide that can be used to successfully control the diseases of tea plants. As a result, tea-producing countries have cut down the uses of fungicides. For example, India recommends only seven fungicides (active ingredients) (Tea Board India 2020), while Sri Lanka lists only five (Advisory Circular PU 1, 2020, TRISL) for managing fungal diseases of tea plants. Emphasis on the rational use of fungicides resulted in residue limits for fungicides in processed tea, including

hexaconazole, propiconazole, copper oxychloride, and carbendazim, that were frequently used for the control of major diseases of tea plants, within the MRLs set by the EU (Karthika and Muraleedharan 2010; Kumar et al. 2004; Manikandan et al. 2009). The global tea industry has been compelled to manage diseases with less reliance on fungicides and to prevent misuse of chemicals, while ensuring stable yield and product quality to meet global and local markets.

In view of climate change and food safety requirements, pesticide residue-driven challenges (nontariff barriers) in tea disease management have put more emphasis on IDM. Strengthening the nonchemical measures in IDM and breeding for disease resistance are the opportunities available to address the above questions. Challenges exist for the commercial use of MBCAs due to their relatively slow activity and variation in their effectiveness. Proper integration of bio-pesticides and other nonchemical methods in IDM and knowledge transfer through extension programs can overcome the issues related to MBCAs.

As the tea plant has a long life cycle, breeding disease-resistant cultivars can deliver long-term solutions for losses caused by fungal diseases. The global tea industry has rich genetic resources that account for about 20,000 germplasm accessions preserved in the major tea-producing countries, including China, India, Sri Lanka, Kenya, and Japan (Ma and Chen 2018). At present, genome sequences of *C. sinensis* var. *assamica* (genome size 3.02-Gb, 30 chromosomes, Xia et al. 2017, genotype TVi, 3.0 Gb, Mondal et al. 2019) and *C. sinensis* var. *sinensis* (Wei et al. 2018) serve as vital resources for studying the genetic basis of disease resistance in tea. The available genetic materials and information will provide opportunities for genetic modifications in developing disease resistance candidates against the major fungal diseases of tea plants. However, self-incompatibility and cross-pollination, as well as a very long breeding cycle of 15 to 25 years (Wang et al. 2018), limit the frequent release of improved tea cultivars for the industry.

Gaps and Future Outlook

The genetic variability of major pathogens causing blister blight, stem canker, and root rots in different geographical regions needs to be worked out in order to project a potential disease control method, as pathogens may have regionally differing adaptation strategies. The current focus on identification of sources of resistance to the above diseases is insufficient. Thus, detailed multiseasonal field trials are required at nursery and field levels to identify resistance sources against major diseases of tea plants. The need for development of molecular markers and their deployment in the breeding programs is also highlighted. Looking at the impact of global climate change on the diseases, attention should be given in breeding programs to develop climate-resilient tea cultivars (cultivars that have a high level of resistance at higher temperature and rainfall) incorporating multiple resistance with greater diversity.

The available information on genes responsible for resistance to blister, gray blight, and brown blight revealed that the tea plant possesses an array of chemical and structural defenses. However, there are still gaps in our knowledge on disease-resistant mechanisms and the genes responsible for resistance to cankers and root rots. The influence of climatic factors on the expression pattern of defense-related genes in tea plants is lacking from a fundamental point of view. Therefore, a deeper understanding of disease resistance mechanisms, and how the fungal pathogens interact with tea bushes, would be helpful to determine durability of resistance in the face of climate change and varying pathogen pressure scenarios.

As far as availability of fungicides and bio-pesticides are concerned, unfortunately very few of the tested products have reached tea planters. This may be due to poor linkage among research, commercialization, and extension activities. There are several technological innovations related to spraying technology that have not yet reached planters. Therefore, improved spraying machinery (with higher efficiency, less chemical usage, and enhanced personnel safety) should be developed. Additionally, to minimize the risk of emergence of fungicide resistance, resistance management strategies should be strengthened. The effective MBCAs, botanicals, and bio-stimulants reported against several pathogens can be used as

components of IDM, after proper validation in tea estates. Therefore, for the deployment of successful IDM packages, coordinated efforts of breeders, researchers, and planters are required.

Studies are needed in tea-growing countries to prevent the rapid spread of pathogens throughout the regions, or from one continent to another continent, and the consequent economic losses. Thus, the present review highlights many questions that are to be addressed, and areas where research is required. In a nutshell, future research should be focused on disease surveillance across the regions, genetic variability in pathogens, sources of resistance, and impact of global climate change on diseases for devising climate smart disease management (CSDM) strategies.

Acknowledgments

The authors sincerely acknowledge Prof. NKB Adikram, National Institute of Fundamental Studies, Sri Lanka, for critical comments, language corrections, and extensive editing of this manuscript. We also thank the anonymous reviewers and feature editor, Mark Gleason, for their contribution in improving the manuscript.

Literature Cited

- Ahmad, I., Mamun, M. N. A., Islam, M. S., Ara, R., Mamdud, M. A. A., and Hoque, A. K. M. R. 2016. Effect of different pruning operations on the incidence and severity of various diseases of tea plant. *J. Biol. Sci.* 24:1-9.
- Ajay, D., and Baby, U. I. 2010. Induction of systemic resistance to *Exobasidium vexans* in tea through SAR elicitors. *Phytoparasitica* 38:53-60.
- Ajay, D., Balamurugan, A., and Baby, U. I. 2009. Survival of *Exobasidium vexans*, the incitant of Blister blight disease of tea, during off season. *Int. J. Appl. Agric. Res.* 115:23.
- Akbar, A., Hamid, F., and Sumreen, S. 2017. Screening *Camellia sinensis* germplasm against grey leaf blight of tea. *J. Agric. Stud.* 5:123-135.
- Anonymous. 2019. International Tea Committee. Annual Bulletin of Statistics, September 2019.
- Arulpragasam, P. V., Addaickan, S., and Kulatunga, S. M. 1987. Recent developments in the chemical control of blister blight leaf disease of tea-effectiveness of fungicides. *Sri Lanka J. Tea Sci.* 56:22-34.
- Baby, U. I. 2001. Pages 315-327 in: Diseases of tea and their management – a review. Pointer Publication, Jaipur.
- Baby, U. I. 2006. Varietal resistance of certain south Indian tea clones to blister blight. Annual Reports of UPASI, 2, Coimbatore, India.
- Balasuriya, A. 2003. 75 years of research and development in Plant Pathology. Pages 165-203 in: Twentieth century tea research in Sri Lanka. W. W. D. Modder, ed. Tea Research Institute of Sri Lanka, Sri Lanka.
- Balasuriya, A. 2008. Common diseases of tea and their management. Pages 173-209 in: Handbook on Tea. Tea Research Institute of Sri Lanka, Talawakelle, Sri Lanka.
- Barthakur, B. K. 2011. Recent approach of tocklai to plant protection in tea in Northeast India. *Sci. Cult.* 77:381-384.
- Bhoral, P., Gohain, B., Gupta, S., Bharalee, R., Bandyopadhyay, T., Das, S. K., Agarwal, N., Singh, H. R., et al. 2012. Molecular analysis and expression profiling of blister blight defense related genes in tea. *Indian J. Genet. Plant Breed.* 72:226-233.
- Bhujel, A., Singh, M., Choubey, M., and Singh, M. 2016. Pest and diseases management in Darjeeling tea. *Int. J. Agric. Sci. Res. (Chennai)* 6:469-472.
- Chakraborty, B. N., Sharma, M., and Das-Biswas, R. 2005. Defense enzymes triggered by *Exobasidium vexans* Masee induce resistance in tea plants. *Indian Phytopathol.* 58:298-304.
- Chakraborty, U., Chakraborty, B. N., Chakraborty, A. P., and De, U. K. 2016. Resistance in tea plants against root rot pathogens induced by arbuscular mycorrhizal fungi and plant growth promoters. *J. Mycopathol. Res.* 54:211-222.
- Chandra, S., Chakraborty, N., Pandab, K., and Acharyaa, K. 2017. Chitosan-induced immunity in *Camellia sinensis* (L.) O. Kuntze against blister blight disease is mediated by nitric-oxide. *Plant Physiol. Biochem.* 115:298-307.
- Chang, H. T. 1981. A taxonomy of the genus *Camellia*. *Acta Scientiarum Naturalium Universitatis Sunyatseni, Monograph Series* 1:1-180.
- Chen, C. N., Lin, C. P., Huang, K. K., Chen, W. C., Hsieh, H. P., Liang, P. H., and Hsu, J. T. 2005. Inhibition of SARS-CoV 3C-like protease activity by theaflavin-3, 3'-digallate (TF3). *Evid. Based Compl. Alternat. Med.* 2:209-215.
- Chen, Y., Qiao, W., Zeng, L., Shen, D., Liu, Z., Wang, X., and Tong, H. 2017. Characterization, pathogenicity, and phylogenetic analyses of

- Colletotrichum* species associated with brown blight disease on *Camellia sinensis* in China. Plant Dis. 101:1022-1028.
- Chen, Y., Zeng, L., Shu, N., Jiang, M., Wang, H., Huang, Y., and Tong, H. 2018. *Pestalotiopsis*-like species causing gray blight disease on *Camellia sinensis* in China. Plant Dis. 102:98-106.
- Cheruiyot, E. K., Mumera, L. M., Ng'etich, W. K., Hassanali, A., Wachira, F., and Wanyoko, J. K. 2008. Shoot epicatechin and epigallocatechin contents respond to water stress in tea. [*Camellia sinensis* (L.) O. Kuntze] Biosci. Biotechnol. Biochem. 72:1219-1226.
- Chong, K. P., and Fazila, M. Y. N. 2012. Potential antagonist organisms against *Poria hypolateritia* of red root disease in tea plantation. Int. J. Biol. 14:457-460.
- De Weille, G. A. 1959. Blister blight control in its connection with climatic and weather conditions. Archs. Tea Cultiv. 20:1-116.
- Dixon, G. R. 2014. Clubroot (*Plasmodiophora brassicae* Woronin) – an agricultural and biological challenge worldwide. Canadian J. Plant Pathol. 36(Sup 1):5-18.
- Edwin, E. R., Ashokraj, S., and Radhakrishnan, B. 2018. Detection of blister blight disease in tea using smartphone and image processing technique. Newsletter 28. UPASI Tea Res. Foundation, Coimbatore, India.
- Elango, V., Kolandasamy, M., Ponnurugan, P., and Subbagoundar, M. 2015. Evaluation of *Streptomyces* spp. for effective management of *Poria hypolateritia* causing red root-rot disease in tea plants. Biol. Control 89:75-83.
- Engelhardt, U. H. 2010. Chemistry of tea. Pages 999-1032 in: Comprehensive natural products II: Chemistry and biology. L. Mender and H. W. Liu, eds. Elsevier, UK.
- FAO. 2014. Guidance document on risk assessment using brew factor for fixation of MRLs of pesticides in tea. FAO Intergovernmental Group on Tea (IGG), Rome, Italy. Retrieved from http://www.fao.org/fileadmin/templates/est/meetings/tea_may14/ISM-14-3-Brew_Policy.pdf
- FAO. 2015. Implications of Maximum Residue Levels (MRLs) on tea trade. Retrieved from <http://www.fao.org/3/a-i4481e.pdf>
- FAO. 2016. Report of the Working Group on Climate Change of the FAO Intergovernmental Group on Tea. Retrieved from <http://www.fao.org/3/a-i5743e.pdf>
- FAO. 2017. World tea production in 2017; Crops/World Regions/Production Quantity from pick lists. Food and Agriculture Organization of the United Nations, Statistics Division (FAOSTAT). Archived from the original on 11 April 2020.

Abhay K. Pandey

Dr. Abhay K. Pandey is a mycologist at the Tea Research Association, India, exploring microbial bio-control agents in the tea ecosystem and understanding their mode of action against fungal pathogens of tea crops. He is also working on plant-pathogen interactions in tea crops. He obtained a Ph.D. on postharvest pathology of pigeon pea seeds from Kumaun University Nainital in 2012. He has authored more than 60 research papers and review articles in peer-reviewed journals. He is associate editor of Journal of Plant Disease and Protection (DPG, Germany), PLoS ONE, and BMC Research Notes for Mycology section, and a potential reviewer of many phytopathology journals, including Plant Disease. He is a member of several plant pathological societies and was recently awarded a Fellowship of the Indian Botanical Society.

Ganga Devi Sinniah

Dr. Ganga Devi Sinniah is a principal research officer and head of the Plant Pathology Division of the Tea Research Institute of Sri Lanka. She obtained a Ph.D. in plant pathology from the University of Peradeniya in 2010. She is the current president of the Sri Lanka Association for Mycology and Plant Pathology (SLAMPP). Her current research interests are the elucidation of plant-pathogen interactions with reference to tea blister blight, management of tea diseases by enhancing host resistance mechanisms and use of bio-pesticides, application of molecular tools in tea disease diagnosis, and resistant screening and disease monitoring by remote sensing. She is also working on pesticide residue management in tea. She has authored more than 40 research papers in peer-reviewed journals.

Azariah Babu

Dr. Azariah Babu is a chief scientist and deputy director (R) at the Tea Research Association, India, involved in integrated pest management of tea crop. He obtained a Ph.D. degree in entomology from the University of Madras in 1992. He has done post-doctoral research at the Swiss Federal Institute of Technology, Zurich, Switzerland. He has been awarded Young Scientist by the Department of Science and Technology (DST), Government of India, New Delhi. He has completed 30 research projects and guided seven students to their Ph.D. degrees. He has authored more than 150 research papers and review articles. He has commercialized microbial products against major pests and tea crops and successfully established a quality control laboratory for microbial pesticides.

Amarjyoti Tanti

Mr. Amarjyoti Tanti is a microbiologist at the Tea Research Association, India, exploring microbial bio-control agents and plant growth-promoting rhizobacteria in the tea ecosystem and their exploitation for pests and disease management. He obtained an M.Sc. degree in microbiology from Gauhati University in 1989, and he has more than 25 years of experience in tea crops. He has authored more than 20 research papers and review articles in peer-reviewed journals.

- FAO. 2018. Intergovernmental Group on Tea, Current Market Situation and Medium-Term Outlook. In: *Committee on Commodity Problems* (CCP: TE 18/CRS1; Vol. CCP:TE 18/CRS1). Retrieved from <http://www.fao.org/3/BU642en/bu642en.pdf>
- Gilbert, C. A., Zhang, N., Hutmacher, R. B., Davis, R. M., and Smart, C. D. 2008. Development of a DNA-based macroarray for the detection and identification of *Fusarium oxysporum* f.sp. *vasinfectum* in cotton tissue. *J. Cotton Sci.* 12:165-170.
- Gnanamangai, B. M., and Ponmurugan, P. 2012. Evaluation of various fungicides and microbial based biocontrol agents against bird's eye spot disease of tea plants. *Crop Prot.* 32:111-118.
- Gulati, A., Gulati, A., Ravindranath, S. D., and Chakrabarty, D. N. 1993. Economic yield losses caused by *Exobasidium vexans* in tea plantations. *Indian Phytopathol.* 46:155-159.
- Gunadi, R. 2001. Blister blight forecasting model based on the relationship between microclimate and disease parameters. M. Sc. thesis, Bogor Agricultural University, Indonesia.
- Gunasekare, M. T. K., and Kumara, J. B. D. A. P. 2005. Tea genetic resources in Sri Lanka. Genetic resources originating from estate selections. *S. L. J. Tea Sci.* 70:69-81.
- Guo, M., Pan, Y. M., Dai, Y. L., and Gao, Z. M. 2014. First report of brown blight disease caused by *Colletotrichum gloeosporioides* on *Camellia sinensis* in Anhui Province, China. *Plant Dis.* 98:284.
- Han, W., Li, X., Yan, P., Zhang, L., and Ahammaed, G. J. 2018. Tea cultivation under changing climatic conditions. In: *Global Tea Science: Current Status and Future Needs*. V. S. Sharma and M. T. K. Gunasekare, eds. Burleigh Dodds Science Publishing, Cambridge, UK.
- Hayat, K., Iqbal, H., Malik, U., Bilal, U., and Mushtaq, S. 2015. Tea and its consumption: Benefits and risks. *Crit. Rev. Food Sci. Nutr.* 55:939-954.
- Hazra, A., Dasgupta, N., Sengupta, C., Bera, B., and Das, S. 2019. Tea: A worthwhile, popular beverage crop since time immemorial. Pages 507-531 in: *Agronomic Crops*. M. Hasanuzzaman, ed. Springer Singapore, Singapore.
- Horikawa, T. 1986. Yield loss of new tea shoots due to grey blight caused by *Pestalotia longiseta* Spegazzini. *Bull. Shizuoka Tea Exp. Stn.* 12:1-8.
- Jayaswalli, K., Mahajan, P., Singh, G., Parmar, R., Seth, S., Raina, A., Swarnkar, M. K., et al. 2016. Transcriptome analysis reveals candidate genes involved in blister blight defense in tea (*Camellia sinensis* (L.) Kuntze). *Sci. Rep.* 6:30412.
- Joshi, S. D., Sanjay, R., Baby, U. I., and Mandal, A. K. A. 2009. Molecular characterization of *Pestalotiopsis* spp. associated with tea (*Camellia sinensis*) in southern India using RAPD and ISSR markers. *Indian J. Biotechnol.* 8:377-383.
- Kabir, S. E., Debnath, S., Mazumder, A., Dey, T., and Bera, B. 2016. *In vitro* evaluation of four native *Trichoderma* spp. isolates against tea pathogens. *Indian J. Fund. Appl. Life Sci.* 6:1-6.
- Karthika, C., and Muraleedharan, N. 2010. Influence of manufacturing process on the residues of certain fungicides used on tea. *Toxicol. Environ. Chem.* 92:1249-1257.
- Karunaratna, K. H. T., Mewan, K. M., Weerasena, O. V. D. S. J., and Abeysinghe, I. S. B. 2013. Microsatellite based approach towards identification of blister blight resistant and susceptible tea (*Camellia sinensis* L. O. Kuntze) cultivars. Page 15 in: *Proc. 6th Annual Scientific Sessions of Institute of Biochemistry, Molecular Biology and Biotechnology (IBMBB)*, University of Colombo, Sri Lanka.
- Karunaratna, K. H. T., Mewan, K. M., Weerasena, O. V. D. S. J., Perera, S. A. C. N., and Edirisinghe, E. N. U. 2020. A functional molecular marker for detecting blister blight disease resistance in tea (*Camellia sinensis* L.). *Plant Cell Rep.* 40:351-359.
- Keith, L., Ko, W. H., and Sato, D. M. 2006. Identification guide for diseases of tea (*Camellia sinensis*). *Plant Disease series PD-33*. University of Hawaii, Honolulu, HI.
- Kerr, A., and de Silva, R. L. 1969. Epidemiology of tea blister blight (*Exobasidium vexans*). *Tea Q.* 40:9-18.
- Kumar, V., Tewary, D. K., Ravindranath, S. D., and Shanker, A. 2004. Investigation in tea on fate of fenazaquin residue and its transfer in brew. *Food Chem. Toxicol.* 42:423-428.
- Kumhar, K. C., and Babu, A. 2019. Biocontrol potency of *Trichoderma* isolates against tea (*Camellia* sp.) pathogens and their susceptibility towards fungicides. *Int. J. Chem. Stud.* 7:4192-4195.
- Langat, J. K., Othieno, W., and Musau, J. M. 1998. Evaluation of some Kenyan tea clones for resistance/susceptibility to *Pestalotiopsis theae* as influenced by some chemical attributes of mature green. *Leaf Tea* 19:6-10.
- Lee, J.-E., Lee, B.-J., Chung, J.-O., Jeong-Ah, H., Lee, S.-J., Lee, C.-H., and Hong, Y.-S. 2010. Geographical and climatic dependencies of green tea (*Camellia sinensis*) metabolites: A ¹H NMR-Based Metabolomics Study. *J. Agric. Food Chem.* 58:10582-10589.
- Li, X., Ahammed, G. L., Li, Z., Tang, M., Yan, P., and Han, W. 2016. Decreased biosynthesis of jasmonic acid via lipoxygenase pathway compromised caffeine-induced resistance to *Colletotrichum gloeosporioides* under elevated CO₂ in tea seedlings. *Phytopathology* 106:1270-1277.
- Li, X., Zhang, L., Ahammed, G. J., Li, Z. X., Wei, J. P., Shen, C., et al. 2017. Stimulation in primary and secondary metabolism by elevated carbon dioxide alters green tea quality in *Camellia sinensis* L. *Sci. Rep.* 7:7937.
- Liu, Y. J., Tang, Q., and Fang, L. 2016. First report of *Nigrospora sphaerica* causing leaf blight on *Camellia sinensis* in China. *Plant Dis.* 100:221.
- Liyanaage, P. N. H., Weerasena, J. O. V. D. S., Liyanaarachchi, C. J., Karunajeewa, N. D. G. P., Mahindapala, J. K. G. P., Mahinda, T. G. N., et al. 2016. Development of species specific ITS markers for the detection of *Botryosphaeria dothidea* and *Lassiodiplodia theobromae* of tea. Pages 107-142 in: *Proceedings of Sixth Symposium on Plantation Crop Research*, 02-04 November 2016, BMICH, Colombo, Sri Lanka.
- Liyanaage, P. N. H., Weerasena, J. O. V. D. S., Liyanaarachchi, C. J., Karunajeewa, N. D. G. P., Mahindapala, J. K. G. P., Wijesundera, R. L. C., and Abeysinghe, I. S. B. 2013. Sensitivity of isolates of *Macrophoma theicola* from untreated and DMI treated tea to hexaconazole. *J. Plant Dis. Prot.* 120:201-204.
- Ma, J.-Q., and Chen, L. 2018. Ensuring the genetic diversity of tea plants. In: *Global Tea Science*. V. S. Sharma and M. T. K. Gunasekare, eds. Burleigh Dodds Science Publishing, Cambridge, UK.
- Maharachchikumbura, S. S. N., Chukeatirote, E., Guo, L. D., Crous, P. W., McKenzie, E. H. C., and Hyde, K. D. 2013. *Pestalotiopsis* species associated with *Camellia sinensis* (tea). *Mycotaxon* 123:47-61.
- Manikandan, N., Seenivasan, S., Ganapathy, M. N. K., and Muraleedharan, N. N. 2009. Leaching of residues of certain pesticides from black tea to brew. *Food Chem.* 113:522-525.
- Mareeswaran, J., Premkumar, R., Asir, S., and Radhakrishnan, B. 2018. Isolation and identification of bacterial strains from different tea growing areas against *Macrophoma* sp. in southern India tea plantation. *J. Plant. Crops* 46:161-168.
- Mitsui, A., Sakai, R., Miwa, K., Shibahara, S., Kurihara, S., and Nagao, K. 2020. Elucidation of the antiviral mechanism of cystine and theanine through transcriptome analysis of mice and comparison with COVID-19 gene set data. *bioRxiv* <https://doi.org/10.1101/2020.06.25.149427>
- Mohhtar, N., and Nagao, H. 2019. Histological description of *Exobasidium vexans* infection on tea leaves (*Camellia sinensis*). *Songklanakarin J. Sci. Technol.* 41:1021-1028.
- Mondal, T. K., Rawal, H. C., Bera, B., Kumar, P. M., Choubey, M., Saha, G., Das, B., Bandyopadhyay, T., Ilango, R. V. J., Sharma, T. R., Barua, A., Radhakrishnan, B., and Singh, N. K. 2019. Draft genome sequence of a popular Indian tea genotype TV-1 [*Camellia assamica* L. (O). Kunze]. *bioRxiv* 762161.
- Muoki, C. R., Maritim, T. K., Oluoch, W. A., Kamunya, S. M., and Bore, J. K. 2020. Combating climate change in the Kenyan tea industry. *Front. Plant Sci.* 11:339.
- Muraleedharan, N., and Chen, Z. M. 1997. Pests and diseases of tea and their management. *J. Plant. Crops* 25:15-43.
- Mur, L. A. J., Hauck, B., Winters, A., Heald, J., Lloyd, A. J., Chakraborty, U., and Chakraborty, B. N. 2015. The development of tea blister caused by *Exobasidium vexans* in tea (*Camellia sinensis*) correlates with the reduced accumulation of some antimicrobial metabolites and the defence signals salicylic and jasmonic acids. *Plant Pathol.* 64:1471-1483.
- Nepolean, P., Jayanthi, R., Mareeswaran, J., and Radhakrishnan, B. 2015. Plant protection development in Tea plantations of South India in the last five decades. *J. Tea Sci. Res.* 5:1-6.
- Omatsu, N., Tomihama, T., and Nonaka, Y. 2012. Incidence of strobilurin and benzimidazole resistant strains of *Pestalotiopsis longiseta*, causal agent of gray blight, and practical control in tea field of Kagoshima Prefecture. *Jpn. J. Phytopathol.* 78:3-9.
- Oniki, M., Narisawa, N., and Ando, Y. 1986. Incidence of strains of the tea gray blight fungi *Pestalotia longiseta* and *P. theae* resistant to benzimidazol fungicides in Japan. *Tea Res. J.* 64:29-33.
- Onsando, J. M., Wargo, P., and Wando, S. W. 1997. Distribution, severity, and spread of *Armillaria* root disease in Kenya tea plantations. *Plant Dis.* 81:133-137.
- Orrock, J. M., Rathinasabapathi, B., and Richter, B. S. 2020. Anthracnose in US Tea: pathogen characterization and susceptibility among six tea accessions. *Plant Dis.* 104:1055-1059.
- Palanisamy, S., and Mandal, A. K. A. 2014. Susceptibility against grey blight disease-causing fungus *Pestalotiopsis* sp. in Tea (*Camellia sinensis* (L.) O. Kuntze) cultivars is influenced by anti-oxidative enzymes. *Appl. Biochem. Biotechnol.* 172:216-223.
- Pallavi, R. V., Nepolean, P., Balamurugan, A., Jayanthi, R., Beulah, T., and Premkumar, R. 2012. *In vitro* studies of biocontrol agents and fungicides tolerance against grey blight disease in tea. *Asian Pac. J. Trop. Biomed.* 2:S435-S438.
- Pandey, A. K., Burlakoti, R. R., Kenyon, L., and Nair, R. M. 2018. Perspectives and challenges for sustainable management of fungal diseases of mungbean [*Vigna radiata* (L.) R. Wilczek var. *radiata*]: A Review. *Front. Environ. Sci.* 6:53.
- Park, S. K., Park, K. B., and Cha, K. H. C. 1996. Gray blight of tea tree caused by *Pestalotia longiseta*. *Korean J. Plant Pathol.* 12:463-465.
- Peiris, C. T., Marasinghe, B. S., Sinniah, G. D., and Fonseka, P. U. 2019. Detection and estimation of tea blister using spectrophotometric analysis. Page 24 in: *The 1st National Symposium of Sri Lanka Association*

- for Mycology and Plant Pathology: Plant Health 2019. 30 August 2019, Kandy, Sri Lanka.
- Phong, N. H., Wattanachai, P., Kasem, S., and Luu, N. T. 2014. Antimicrobial substances from *Chaetomium* spp. against *Pestalotia* spp. causing grey blight disease of tea. J. Agric. Technol. 10:863-874.
- Ponmurugan, P., and Baby, U. I. 2007. Evaluation of fungicides and biocontrol agents against *Phomopsis* canker of tea under field conditions. Australas. Plant Pathol. 36:68-72.
- Ponmurugan, P., Gnanamangai, B. M., and Manjukurambika, K. 2019. Architectural effect of different tea clones on the development of blister blight disease. J. Appl. Bot. Food Qual. 92:7-14.
- Ponmurugan, P., Manjukurambika, K., Elango, V., and Gnanamangai, B. M. 2016. Antifungal activity of biosynthesized copper nanoparticles evaluated against red root-rot disease in tea plants. J. Exp. Nanosci. 11:1019-1031.
- Prathibhani, H. M., Kumarihami, C., and Song, K. J. 2018. Review on challenges and opportunities in global tea industry. J. Korean Tea Soc. 24:79-87.
- Premkumar, R., Ajay, D., and Muraliedharan, N. 2009. Biological control of tea diseases- A Review. Pages 223-230 in: Role of Biocontrol Agents for Disease Management in Sustainable Agriculture. Research India Publications, Delhi, India.
- Premkumar, R., Sanjay, R., and Ponmurugan, P. 2002. Forecasting of blister blight disease of tea. Pages 535-540 in: Proc. PLACROSYM XIV, Plantation Crops Research and Development in the New Millennium.
- Punyasi, P. A. N., Abeysinghe, S. B., and Kumar, V. 2005. Preformed and induced chemical resistance of tea leaf against *Exobasidium vexans* infection. J. Chem. Ecol. 31:1315-1324.
- Rabha, A. J., Naglot, A., Sharma, G. D., Gogoi, H. K., Gupta, V. K., Shreemali, D., and Veer, V. 2016. Morphological and molecular diversity of endophytic *Colletotrichum gloeosporioides* from tea plant, *Camellia sinensis* (L.) O. Kuntze of Assam, India. J. Genet. Eng. Biotechnol. 14:181-187.
- Radhakrishnan, B., and Baby, U. I. 2004. Economic threshold level for blister blight of tea. Ind. Phytopath. 57:195-196.
- Ramashish, K. 2015. Characterization and application of some plant extracts for controlling important foliar fungal diseases of tea. <http://hdl.handle.net/10603/54449>
- Rattan, P. S., and Sobrak, A. 1976. Incidence of *Phomopsis* stem and branch canker. Annual report, The Tea Research Foundation of Central Africa, Malawi.
- Rayati, D. J. 2011. The effectiveness of various biological control agents on blister blight disease (*Exobasidium vexans* Massee) on tea. Indones. J. Tea Cinchona Res. 14:8-15.
- Saha, D., Dasgupta, S., and Saha, A. 2005. Antifungal activity of some plant extracts against fungal pathogens of tea (*Camellia sinensis*). Pharm. Biol. 43:87-91.
- Sanjay, R., Baby, U. I., Sasidhar, R., and Premkumar, R. 2003. Impact of harvesting methods on grey blight incidence. Newsl. UPASI Tea Res. Found. India. 13:14-26.
- Sanjay, R., Ponmurugan, P., and Baby, U. I. 2008. Evaluation of fungicides and biocontrol agents against grey blight disease of tea in the field. Crop Prot. 27:689-694.
- Saravanakumar, D., Vijayakumar, C., Kumar, N., and Samiyappan, R. 2007. PGPR induced defense responses in the tea plant against blister blight disease. Crop Prot. 26:556-565.
- Sarmah, S. R., Dutta, P., Begum, R., Tanti, A. J., Phukan, I., Debnath, S., and Barthakur, B. K. 2005. Microbial bioagents for controlling diseases of tea. Pages 767-775 in: Proceedings of 2005 International Symposium on Innovation in Tea Science and Sustainable Development in Tea Industry, 11-15 November, Chinese Academy of Agricultural Science, Hangzhou, China.
- Senthilkumar, P., Suganthi, M., and Mandal, A. K. A. 2019. Differential expression of pathogenesis-related proteins determines the disease tolerance and sensitivity in tea cultivars during grey blight disease development. Pak. J. Phytopathol. 31:163-170.
- Sharma, N., Muthamilarasan, M., Prasad, A., and Prasad, M. 2020. Genomics approaches to synthesis plant-based biomolecules for therapeutic applications to combat SARS-CoV-2. Genomics 112:4322-4331.
- Sierotzki, H., and Scalliet, G. 2013. A review of current knowledge of resistance aspects for the next-generation succinate dehydrogenase inhibitor fungicides. Phytopathology 103:880-887.
- Sinniah, G. D. 2018. Diseases affecting tea plants. In: Global Tea Science: Current Status and Future Needs. V. S. Sharma and M. T. K. Gunasekare, eds. Burleigh Dodds Science Publishing, Cambridge, UK. <http://dx.doi.org/10.19103/AS.2017.0036.12>
- Sinniah, G. D., Kumara, K. L. W., Karunajeewa, D. G. N. P., and Ranatunga, M. A. B. 2016. Development of an assessment key and techniques for field screening of tea (*Camellia sinensis* L.) cultivars for resistance to blister blight. Crop Prot. 79:143-149.
- Sinniah, G. D., Munasinghe, C. E., Mahadevan, N., Jayasinghe, S. K., and Kulatunga, D. C. M. 2017. Recent incidence of collar canker and die-back of tea (*Camellia sinensis*) caused by *Fusarium solani* species complex in Sri Lanka. Australas. Plant Dis. Notes 12:41.
- Sinniah, G. D., Wickramasinghe, N. S. W., and Samarasekara, L. A. A. S. 2014. Active defense responses associated with resistance of tea to blister blight and induction of resistance in disease management. In: Proceedings of Fifth Plantation Crop Symposium, 15-17 October, BMICH, Colombo, Sri Lanka.
- Takeda, Y. 2002. Genetic analysis of tea gray blight resistance in tea plants. Jpn. Agric. Res. Q. 36:143-150.
- Tea Board India. 2020. Plant Protection Code 2020, version 12.0. Tea Board India, Ministry of Commerce and Industry, Govt. of India, West Bengal, India.
- Thakur, B. R., and Masand, S. 2015. Efficacy of Nativio 75 WG against blister blight in tea. [*Camellia sinensis* (L.) O. Kuntze] Himachal J. Agric. Res. 41:86-88.
- Tubbs, F. R. 1946. Blister Blight. Tea Q. 18:90.
- Uddin, J. M., Shahiduzzaman, M., and Ahmed, I. 2005. Effect of pruning cycle on the yield of mature tea. Int. J. Sust. Agric. 1:82-85.
- Venkata, R. C. S. 1979. *Phomopsis* collar canker - A limiting factor to use of clonal material. Pages 146-151 in: The 2nd Plantation Crops Symposium (PLACROSYM II), Ootacamund, India.
- Voora, V., Bermúdez, S., and Larrea, C. 2019. Global Market Report: Tea. Sustainable Commodities Marketplace Series, International Institute for sustainable Development. Retrieved from <https://www.iisd.org/system/files/publications/ssi-global-market-report-tea.pdf>
- Walters, D. R., Paterson, L., Walsh, D. J., and Havis, N. D. 2009. Priming for plant defense in barley provides benefits only under high disease pressure. Physiol. Mol. Plant Pathol. 73:95-100.
- Wang, L., Wang, Y., Cao, H., Hao, X., Zeng, J., Yang, Y., and Wang, X. 2016. Transcriptome analysis of an anthracnose-resistant tea plant cultivar reveals genes associated with resistance to *Colletotrichum camelliae*. PLoS One 11:e0148535.
- Wang, L. Y., Wei, K., Jiang, Y. W., Cheng, H., Zhou, J., He, W., and Zhang, C. C. 2011. Seasonal climate effects on flavanols and purine alkaloids of tea (*Camellia sinensis* L.). Eur. Food Res. Technol. 233:1049-1055.
- Wang, X., Hao, X., Wang, L., and Yajun, Y. 2018. Mapping and exploiting the tea genome In: Global Tea Science. V. S. Sharma and M. T. K. Gunasekare, eds. Burleigh Dodds Science Publishing, Cambridge, UK.
- Wei, C., Yang, H., Wang, S., Zhao, J., Liu, C., Gao, L., Xia, E., Lu, Y., Tai, Y., et al. 2018. Draft genome sequence of *Camellia sinensis* var. *sinensis* provides insights into the evolution of the tea genome and tea quality. Proc. Nat. Acad. Sci. 115:E4151-E4158.
- Xia, E. H., Zhang, H. B., Sheng, J., Li, K., Zhang, Q. J., Kim, C., Zhang, Y., et al. 2017. The tea tree genome provides insights into tea flavor and independent evolution of caffeine biosynthesis. Mol. Plant 10:866-877.
- Yamada, K., Sonoda, R., and Ishikawa, K. 2016. Population genetic structure of QoI-resistant *Pestalotiopsis longiseta* isolates causing tea gray blight. Plant Dis. 100:1686-1691.
- Yang, H., Xue, X., Li, H., Apandi, S. N., Tay-Chan, S. C., Ong, S. P., et al. 2018. The relative antioxidant activity and steric structure of green tea catechins - A kinetic approach. Food Chem. 257:399-405.
- Yao, L. H., Jiang, Y. M., Datta, N., Singanusong, R., Liu, X., Duan, J., Raymont, K., Lisle, A., and Xu, Y. 2004. HPLC analyses of flavanols and phenolic acids in the fresh young shoots of tea (*Camellia sinensis*) grown in Australia. Food Chem. 84:253-263.
- Yoshida, K., Ogino, A., Yamada, K., and Sonoda, R. 2010. Induction of disease resistance in Tea (*Camellia sinensis* L.) by plant activators. Jpn. Agric. Res. Q. 44:391-398.
- Yoshida, K., and Takeda, Y. 2006. Evaluation of anthracnose resistance among tea [*Camellia sinensis*] genetic resources by wound-inoculation assay. Jpn. Agric. Res. Q. 40:379-386.
- Zeng, L., Watanabe, N., and Yang, Z. 2018. Understanding the biosyntheses and stress response mechanisms of aroma compounds in tea (*Camellia sinensis*) to safely and effectively improve tea aroma. Crit. Rev. Food Sci. Nutr. 59:2321-2334.
- Zhu, J., Pan, Z., Wang, H., Huang, P., Sun, J., Qin, F., and Liu, Z. 2019. An improved multi-temporal and multi-feature tea plantation identification method using sentinel-2 imagery. Sensors (Basel Switz.) 19:2087.