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Late Blight of Potato (*Phytophthora infestans*) II: Employing Integrated Approaches in Late Blight Disease Management

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Abstract
Late blight of potato is a yield reducing and one of the most costly diseases of potato and other plants belonging to family Solanaceae. Induced by *Phytophthora infestans*, the disease prevails throughout the world where potato and other Solanaceous crops are cultivated. *P. infestans* has a broad host range; however, the most severe effects of late blight are more evident on its principal hosts – potato and tomato. Cool and humid environmental conditions ideally propagate the pathogen which may result in severe disease outbreaks with substantial crop losses. Currently, extensive use of chemical fungicides is the only effective measure to control late blight; however, their use offers public, environmental and economic challenges. Thus, it is necessary to address these challenges by employing integrated disease control strategies. This review highlights all those combined techniques which may be effective in controlling late blight of potato while sustaining environment, public health and economic costs incurred by the disease.
Keywords: Integrated disease management, Population dynamics, Fungicides, Environmental hazards, Yield losses.

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INTRODUCTION

Solanaceae is an important plant family which has a diverse group of plants – ranging from wild species to several economically important cultivated crops. Potato belongs to this family which is an important cultivated crop with significant contribution to global food demands, trade and economic benefits. More than one billion people throughout the world are dependent on potato consumption (Anwar *et al.,* 2015) which highlights its popularity and importance. Global potato production in 2014 was revealed as 382 million tonnes with major shares from the developing countries (FAOSTAT 2017). Currently, China (Mainland) and India are the leading potato producers of the world accounting for 95.5 and 46.3 million tonnes followed by the Russian Federation with production 31.5 million tonnes (FAOSTAT 2017). Increase in potato productivity during the past decade is the result of cultivation of high yielding varieties, high fertilizers inputs and increased area for harvest. In Pakistan, potato production (2.9 million tonnes in 2014) is not as promising as it is in other South Asian countries particularly in India and Bangladesh which produced 46.3 and 8.9 million tonnes potato during the same period.

Potato production has spacious potential for increase in future; however, there are several diseases of fungal, bacterial and viral origin in addition to parasitic nematodes which have drastic effects on yield and production of this important crop (Arora and Khurana, 2004). Among the diseases, late blight, caused by *P. infestans*, is one the most widely occurring disease which has tremendous impact on the yield, productivity and profitability of potato (Majeed *et al.,* 2017). Crop losses in response to late blight are particularly enormous in areas where heavy rainfall and low temperature are common. In order to reduce losses in crop productivity, synthetic fungicides of diverse chemical nature are used as aerial sprays on foliage of potato which can manage the negative effects of late blight; however, based on the toxic effects of these chemicals, they can harm public health, pose environmental pollution and incur huge costs (Majeed *et al.,* 2011, 2017). To minimize crop losses as a result of late blight and environmental problems posed by fungicides application, sustainable approaches for late blight management are needed. Integrated disease approach- a set of different controlling practices employed in proper timing before and after the diseases onset, and which aims at reducing infection rate of the pathogen, impact of source of inoculation and the interaction time between the host and pathogen (Nutter, 2007) – is advantageous over single controlling practice because combined approaches have maximum impact on the pathogen and cover many aspect of the disease control. Grünwald *et al*. (2000) documented that fungicides forecasting systems and host resistance contributed significantly to control of late blight and resulted in minimal use of fungicides. Garrett *et al*. (2001) asserted that cultivation of blight resistant varieties of potato and intercropping of diverse genotypes could be helpful in minimizing crop losses and reliance of fungicides to some extent. Kirk *et al*. (2003) stated that host resistance to *P. infestans* could be potentially useful in reducing fungicides rates. Cooke *et al*. (2011) stressed for the use of integrated control measures and low fungicides use to manage late blight disease. Majeed *et al*. (2015) advocated the use of plant extracts and natural compounds as alternative treatments for controlling late blight and associated crop losses. This paper reviews the integrated control strategies used for late blight control with sustainable production gains of the crop and less harms to the environment.

POTATO LATE BLIGHT AND CONTROL BY FUNGICIDES APPLICATION

Disease and the pathogen's cycle

Late blight of potato caused by *P. infestans* has received considerable attention of plant pathologists in the current century since its role in the Irish starvation in 1845s which ended with a million deaths and migration of the Irish people out of Ireland (Nowicki *et al.,* 2012). Since then, late blight epidemics have been frequently observed in Europe (Hannukkala *et al.,* 2007), America (Fry and Goodwin, 1997), Asia (Chunwongse *et al*., 2002), Africa (McLeod *et al.,* 2001) and many other regions. The pathogen parasitizes diverse hosts in family Solanaceae; however, potato and tomatoes are drastically affected (Flier *et al.,* 2003; Majeed *et al*., 2017). Typically, late blight symptoms on foliage and stems as green brown or yellow spots which becomes necrotic regions as the growth of pathogen occurs may appear few hours after infection with *P. infestans* which generally depend on the environmental conditions and host susceptibility (Fry, 2008; Majeed *et al*., 2017). Accelerated by cool temperature and moisture availability, *P. infestans* rapidly propagate its mycelia producing thousands of lemon shaped sporangia on sporangiophores which serve as dispersal means and asexual infection agents aerially (Nowicki *et al*., 2012). Sporangia are carried from the infected plants to healthy plant by water and air and when settle on plants leaves and stem, they either directly germinate by germ-tube under temperature range between 20 and 25°C or indirectly by the release of many zoospores when temperature is low i.e., range between 10 and 15°C (Fry, 2008). Lesions and disease symptom appear at this stage and may take 2-3 days for first necrotic lesion is visible (Fry, 2008). The asexual life cycle may repeat several times a week if environmental conditions allow to do so (Nowicki *et al*., 2012). Sporangial survival for next infection is restricted to host tissues and little is known whether they can remain viable in soil or other dead matter. However, it is well established that during growing season when host plants are available, asexual life cycle of *P. infestans* predominates causing several disease cycles (Drenth *et al*., 1993) (Figure 1).

P. infestans exhibits heterothallism with two compatible mating types, A1 and A2 and for sexual reproduction, the presence of both mating types is required (Ristaino, 2002; Yuen and Andersson, 2013). Sexual reproduction may proceed both under natural conditions when two opposite thali come in contacts as well as in artificial inoculation by growing mixtures of both mating types and result is the formation of oospores (Drenth *et al*., 1995). However, for sexual reproduction and production of substantial number of oospores, larger proportions of both mating types should be present in close proximity (Yuen and Andersson, 2013). Oospores have thick walls and are larger than sporangia with potential capacity for survival in soil for long periods unlike sporangia which remain viable only on host tissues (Nowicki *et al*., 2012). Thus, oospores are potential source of infection for next season plants as well as source of genetic variation and development of traits necessary for coping with environmental changes, host resistance and fungicides resistance (Widmark *et al*., 2011). Oospores germinate to form sporangiophores which bear sporangia that may switch to asexual cycle by releasing zoospores, although germination of oospores is influenced by several environmental factors.

Control of the disease by fungicides application

Late blight of potato is effectively controlled by applying chemical fungicides at suitable rates and intervals depending on the climatic conditions and diseases severity (Majeed *et al*., 2014b). Effectivity of fungicides in management of late blight depend on the proper use and time of application. After the great Irish potato famine caused by *P. infestans*, first effective fungicide used for diminishing late blight atrocities was Bordeaux mixture, a copper sulphate chemical which has several environmental implications (Haverkort *et al*., 2008). Progress in synthetic chemistry in the last few decades has resulted in formulation of advanced chemicals which are relatively less hazardous than has now enabled manufacturers to Bordeaux mixture; however, their excessive use also pose ecological, environmental and financial problems. The most commonly used fungicides for controlling late blight are cymoxanil + mancozeb, cymoxanil + famoxadone and fluazinam under different trade names (Haverkort *et al*., 2008). Every year, substantial quantities of different fungicides and pesticides are used in agriculture for controlling palnt pathogens and pests of which more than 30% accounts for late blight fungicides (Naerstad *et al*. 2007).

Though, fungicides application is an effective measure to check late blight at the earliest; however, public health, environmental problems and financial costs associated with it is a major agricultural issue (Majeed *et al*., 2014a; Majeed *et al*., 2017). Late blight fungicides along with other pesticides are potent sources for poisoning of farmers, children and other non-target animals and are one of the leading sources of air, soil and water pollution. Monetary costs due to late blight fungicides is considered as more than 3 billion dollars per year globally (Haverkort *et al*., 2008). Moreover, due to several migration events of *P. infestans* and sexual reproduction, new genotypes of the pathogen with more aggressiveness and potentials to overcome fungicides efficacy have been frequently appearing which has further complicated late blight control (Vossen *et al*., 2005; Majeed *et al*., 2014b). Although it seems non feasible to completely relinquish fungicides application, its use however, may be significantly reduced by adopting integrated strategies.

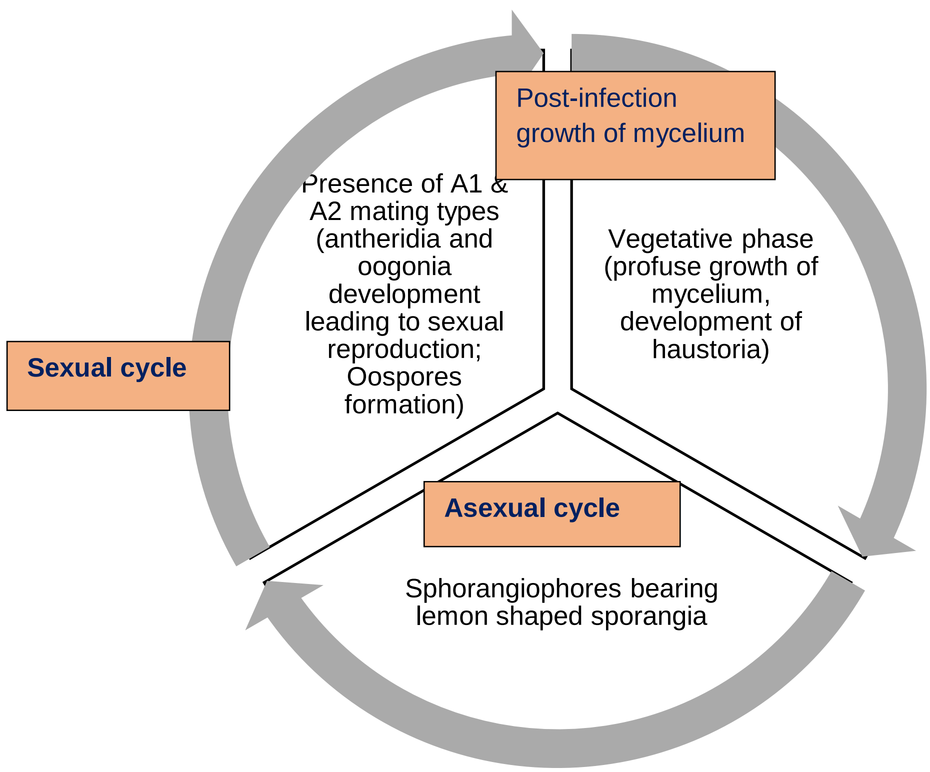

Fig. 1. Asexual and sexual life cycle of *P. infestans*

INTEGRATED DISEAESE APPROACHES FOR LATE BLIGHT CONTROL

Integrated disease approach includes all the available practices which can be utilized for maximizing the control of a disease. Integrated approach does not rely on a single factor necessary for disease control, rather it involves a set of components that have specific application under specific circumstances. Cultural practices, cultivation of resistant varieties, intercropping of mix genotypes which have variable susceptibility, fungicides application at appropriate timing, understanding of weather and careful monitoring of the disease incidence are some of the important components of integrated disease management approaches (Small *et al*., 2015; Islam *et al*., 2016). For operation of successful integrated control strategies, understanding of the disease trainable – a conceptual disease model which correlates the interactions among the pathogen, host and its environment – is crucial (Scholthof, 2007). The disease triangle explains that favorable environmental conditions coupled with host susceptibility have stimulatory outcomes for the disease development. Similarly, the host pathogen interactions become severe if the pathogen is aggressive. Under environmental conditions not favorable for the disease progress, the pathogen experiences difficulties in damaging the host. Less severe effects are likely to be observed if the pathogen is weakly aggressive and the host offer resistance to the disease development (Figure 2).

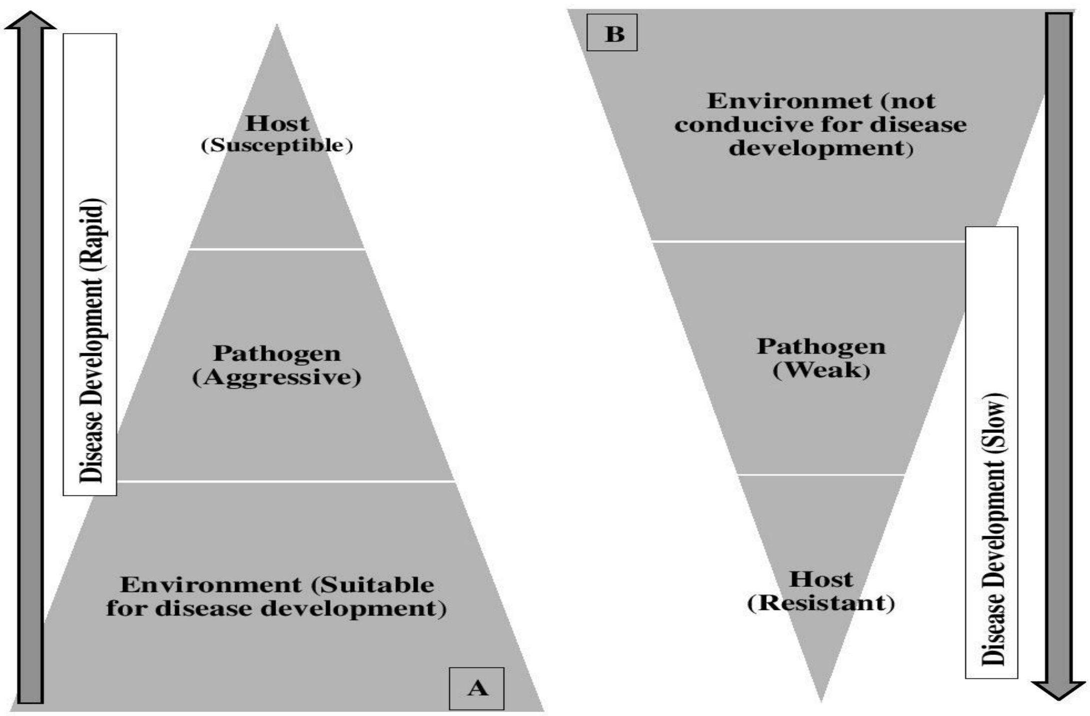

Fig. 2. Disease triangle for environment-pathogen-host interaction. A- favorable environment, susceptible host and aggressive pathogen increases disease severity; B- non-conducive environment, weak pathogen and resistant host slow down the disease progress

Cultural control

Cultural practices include removal of the inoculation sources (infected plat tissues and debris), cultivation of disease free seeds, soil and plant management, intercropping of different potato varieties and nutrient management (Kirk *et al*., 2005). Removal of inoculum sources from fields after harvest and before cultivation in the next season is one of the prime factors in the onset, progress and control of late blight. Zwankhuizen *et al*. (1998) described refused piles as the major source of late blight infection while previously infected potato and tomato fields served as a midseason sources of disease spread for adjacent fields. Powelson *et al*. (2002) regarded volunteer potato, cull piles and infected seed tubers as major sources of disease inoculum and stressed on their destruction for avoiding potential disease outbreak. One of the best strategies to minimize the chances of get infected fresh potatoes from these sources, elimination of volunteer potato, refuse piles and cultivation of diseased free tubers is strongly needed which could be carried out by burning or manual removal. Both, burning and manual removal of sources of inoculum is feasible only in small farm system. Under large scale farms, farmers will face tough challenges to remove these inoculation sources; thus other strategies like crop rotation in such conditions seems a suitable alternatives because cultivation of non-host plant in infected fields for long period reduces the chances of sporangial survival.

Host resistance

One of the most widely focused components of integrated disease management is the development of host resistance and cultivation of already available resistant cultivars. Unfortunately, currently there are no cultivars of potato with complete resistance to *P. infestans*. During the past two decades, breeding efforts have been made for introgression of resistance genes from wild species of solanaceae into cultivated potato; however, successes of such efforts have been debated because of the appearance of new genotypes of *P. infestans* which have successfully overcome the resistance provided by introgressed genes (Ballvora *et al*., 2002). During that period, more than 40 late blight resistance (LR) genes were determined from different wild species (Śliwka and Zimnoch-Guzowska, 2013) which have potential application in breeding programs; however, major issues with resistance genes are their race specific nature which provide resistance to a particular race of the pathogen and hence prove temporal and non-durable (Kamoun *et al*., 1999). On the other hand, non-host resistance is durable and offer durable defense to host against the invading pathogens but unfortunately successes of the studies addressing non-host resistance against *P. infestans* in potato cultivars have not been promising so far (Vleeshouwers *et al*., 2001). Thus, for achieving durable resistance in potato to different races of *P. infestans* further elaboration of cisgenic techniques is imperative.

Fungicides application

Without fungicides application, control of late blight of potato does not seem achievable. Thus fungicides application is an active component of integrated disease control. Knowledge about the biology of the pathogen, prevailing environmental conditions in potato growing areas, degree of susceptibility of potato cultivars to late blight and mode of action of fungicides can help farmers to select proper fungicides and to apply them at suitable time at suitable dosages. Cooke *et al*. (2011) argued that fungicides could effectively be employed as active component of integrated disease management if their nature, mode of activity and their relative influence on foliage, stem and tuber infection caused by *P. infestans* could be taken into account. Evenhuis *et al*. (2016) described that standard application rate (7 d) or even lower frequencies of fungicides might be helpful in reducing disease damage if other cultural control measures are addressed. Since the emergence of new strains of *P. infestans* which exhibit fungicides resistance, selection of suitable fungicides and timing of fungicide spray have become even more crucial for effective control of late blight. In regions where population of *P. infestans* comprise fungicides resistant isolates, application of more than one types of fungicides and changes in spray schedule seems a promising approach along with utilizing integrated control measures such as cultivation of resistant cultivars of potato.

CONCLUSION

Late blight of potato and tomato offer several challenges to crop growers ranging from crop losses and financial burdens to health issues, environmental and social disturbances. The disease is mainly managed by fungicides sprays which have drastic impact on environment besides financial costs. A good approach to reduce the fungicides application and late blight outcomes on crops, integrated disease control approaches such as cleaning of pathogen's sources, use of disease frees seeds and resistant cultivars is needed. Training and educating farmers about the basic characteristics of the pathogen and environmental influences on the disease development is necessary because knowledge about the pathogen, host, environment and sources from where infection can occur is important in modification of cultivation sequence of the host and employment of necessary control arrangements.

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CONFLICT OF INTEREST

There is no conflict of interest.

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