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REVIEW ON EPIDEMIOLOGY, SAMPLING TECHNIQUES, MANAGEMENT STRATEGIES OF LATE BLIGHT (*Phytophthora infestans*) OF POTATO AND ITS YIELD LOSS

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AUTHOR'S CONTRIBUTION

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ABSTRACT

Late blight of potato is the most important polycyclic oomycete disease globally and is caused by *Phytophtora infestans*, which resulted in yield loss ranged from 5-100%. The pathogen spores can be spread via wind, rain splash, seed tubers, farm equipment, and animals. Losses due to *Phytophthora infestans* have been estimated to € 12 billion per annum, of which the losses in developing countries have been estimated around € 10 billion per annum. Disease assessment is done at the stage at which the crop tends to be most vulnerable to late blight epidemics, which is one to two weeks after flowering (45 to 65 days old) and each sample is assessed by the standard scale 1-100%. Late blight of potato can be managed effectively through the integration of all strategies such as removal of infected volunteer potato and other hosts, adjusting the date of planting and clean seed tuber, use of resistant varieties, seed dressing fungicides like metalaxyl, and use of Pseudomonas and Bacillus biosurfactants etc. Therefore, it is valuable to use integrated disease management to tackle the problem as best management approach.

Keywords: Integrated disease management; Late blight; *Phytophtora infestans*; Polycyclic; Yield loss.

1. INTRODUCTION

Late blight disease, caused by *Phytophthora infestans*, is a major problem in potatoes worldwide. Potato late blight, caused by the oomycete pathogen *Phytophthora infestans* Mont. (de Bary), first occurred in Europe in the 1840s when it led to the devastating Great Irish Potato Famine. It is probably the single most important disease of potatoes and tomatoes worldwide [1]. Worldwide losses due to late blight are estimated to exceed $ 5 billion annually and thus the pathogen is regarded as a threat to global food security [2].

Phytophthora infestans is the best known, most studied and still among the destructive of all potato diseases of the species of *Phytophthora*. Over 160 years later, it continues to pose a major threat to potato production, particularly in the cooler, wetter northern European countries despite the efforts of potato breeders and fungicide producers [3]. Similarly, in Ethiopia, the damaging impact of this dreaded pathogen is increasingly becoming a serious problem in potato production and the disease is threat to food security. In Ethiopia, potato yield loss caused by *Phytophtora infestans* ranges between 29–100%, depending on variety used [4].

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The pathogen is hemibiotrophic, not obligate parasite, and can survive in soil as oospores in the absence of the host. The genus *Phytophthora,* belongs to the Oomycetes, which are unrelated to true fungi. The genus *Phytophthora* contains some species (including *P. infestans*) that are heterothallic (A1 and A2 mating types) [5]. The mycelium produces branched sporangiophores that produce lemon-shaped sporangia at their tips. At the places where sporangia are produced; the sporangiophores form swellings that are characteristic for this fungus [6]. The oomycete *Phytophthora infestans* (Mont.) de Bary can reproduce asexually and sexually. Sexual reproduction in this heterothallic fungus only occurs when thalli of opposite mating type (Al andA2) mate. Mating results in the production of oospores in host plant tissue. Oospores are persistent, thick-walled structures which can over winter in the soil in the absence of a host.

The late blight disease affects all plant parts especially leaves, stem and tubers. Pale green water-soaked spots (2–10 mm) appear mostly on the margin and tips. In moist weather, spots may appear anywhere on the leaves, enlarge rapidly and turn necrotic and black killing the entire leaf instantly. On the corresponding lower side, whitish cottony growth containing millions of sporangia forms around the dead area in a ring pattern. Generally, late blight appears on lower most leaves of the plant which goes unnoticed from a distance. Slowly, the disease spreads to the middle and then upper leaves. Subsequently it spreads whole plants and near of the plants. The disease spreads faster and the entire crop gets killed as if burnt by fire. The heavily infected field gives fetid odor which can be felt from a distance. Light brown lesions develop which elongates and encircles the stem and petioles breaking them and killing the plant/leaves instantly [7].

Stem infection is more severe under high temperature and relative humidity conditions. Symptoms of stem blight are observed more in last ten years. On the other hand, rusty brown discoloration of the flesh is the typical symptom of late blight. It can attack tubers when spores are washed down in to the soil. Badly infected filed generally give off a distinctive smell of rotting tissue. Normally, late blight infected tubers are hard but associated secondary pathogens may set in soft rot symptoms [8]. This review paper is therefore, written to fill the gap of potato late blight occurrence and yield loss, sampling technique and management strategies. This paper is organized and written through the use of various secondary sources that have been conducted globally. These sources were collected from different published journal articles, books, proceedings, research reports and manuals.

2. LATE BLIGHT AND ITS MANAGEMENT

2.1 Disease Cycle

Phytophthora infestans has two life cycles: an efficient asexual cycle, and sexual cycle. Infection usually starts with deposition of sporangium on a living host leaf or stem. Germ tubes can also form secondary sporangia, which may serve to increase the longevity of the spore [9]. Sporangia germinates directly through production of germ tube that penetrates the host tissue, and production and release of 6 to 12 motile zoospores in warmer and cooler conditions, respectively.

Sporangia may germinate at temperatures between 7 and 13°C when free water is present on leaves. After penetration, threadlike filaments which is hyphae begins intracellular colonization of host tissue. Haustoria develop and extract nutrients from within the cells of host and thus destroy the plant tissue, which is giving rise to necrotic lesion. After couple of days, sporangiophores emerge around the edge of the lesion and the sporangia may be dispersed by the wind to cause new foliar infection in the same crop and neighboring fields. The rain and irrigation water splashed them on to other leaves and down in to the soil and infect tuber tissue. Older infected cells die while the mycelium continues to spread into fresh tissue. In any case, as the disease develops, established lesions enlarge and new ones develop, often killing the foliage and reducing potato tuber yields [6] (Fig. 1).

Asexual cycle can be repeated every 5 to 7 days and it is an important phenomenon for rapid polycyclic epidemics. In sexual reproduction, *Phytophthora infestans* is heterothallic, to which two mating types are required. It involves the production of male sex organ (Antheridium) and a female sex organ (oogonium) that may contain one or several eggs. Meiosis occurs within these sex organs and fertilization is achieved by the transfer of a single haploid nucleus to each haploid egg, and this leads to the development of oospores [8].

The development of late blight epidemics depends greatly on the prevailing humidity and temperature during the different stages of the life cycle of the pathogen. The oomycete can complete many reproductive cycles in a season, accounting for the rapid increase of disease once it becomes established in a field. When conditions are continuously wet all tender aboveground parts of the plants become blight and rot away giving off a characteristic odor. Entire potato plants and plants in entire fields may become blighted and die in a few days or a few weeks. In dry weather the activities of the pathogen are slowed or stopped. Existing lesions stop enlarging, turn black, curl, and wither, and no oomycete appears on the underside of the leaves. When the weather becomes moist again the oomycete resumes its activities and the disease once again develops rapidly [6].

2.2 Source and Environmental Requirements of Late Blight

Late blight is one of the most popular, most studied and most serious disease of potato in many regions of the world. The primary sources of inoculum that can be responsible for the outbreak of *P. infestans* are latently infected seed tubers, infected tubers (cull piles and volunteer potatoes), and closely related weed hosts. But latently infected seed tubers are the most important source of primary inoculums leading to epidemic disease development. Late blight disease can be airborne [10], soil-borne, and seed-borne [11].

The disease can destroy the entire foliage quickly causing reduced tuber yields. Sporangia released from infected plants are known to be capable of wind-borne migration for over several kilometers [12]. In Ethiopia, potato seed tubers are commonly produced through field multiplication of vegetative produced seed tubers. However, field multiplication of vegetative propagated seeds tubers leads to high late blight pressure and the production of poor-quality seed tubers [13].

Wherever, both mating types A1 and A2) is existed oospore formation take place and oospore also has the potential to cause and initiate the disease. Sporangia are formed wide range of temperature (3 to 26°C) and optimum is 18–22°C. The sporangia are germinated by two ways process i.e. indirect and direct germination. It depends mainly on temperature and indirect germination generally occurs at temperatures of 6 to 15°C (optimum 12°C) by means of sporangia produces zoospores. Direct germination takes place under warm temperature and a range of 4 to 30°C (optimum 25°C). High relative humidity (>90%) is required for spore formation, germination and infection; whereas >80% is essential for lesions expansion. Extreme light is harmful for *P. infestans* and sometimes sporangia may be killed due to extreme light. Cloudy weather is favorable for late blight. The cool (12–15°C) and high humidity (>90%) weather with heavy dews or rains alternating with warm (18–20°C) moist period favor for rapid development of disease. Infection and disease development are observed a range of 7.2–26.6°C [14].

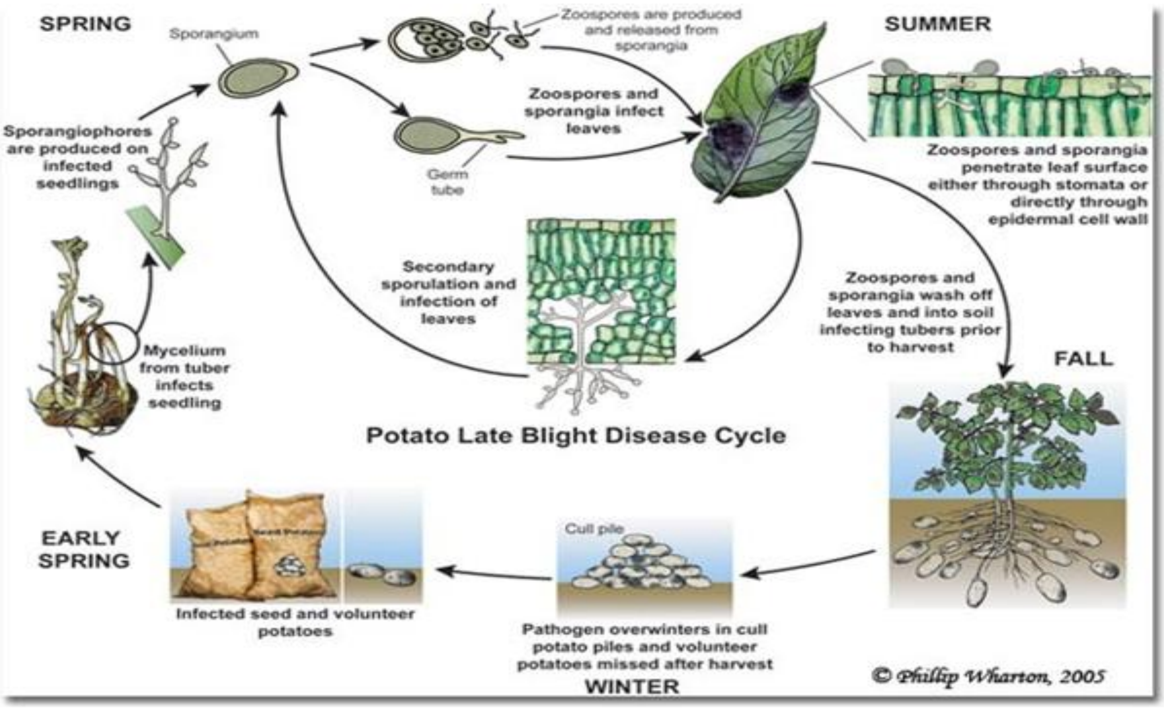

Fig. 1. The life cycle of the late blight pathogen *Phythophtora infestans* [6]

2.3 Disease Epidemiology and Its Spread

The first symptoms of late blight in the field are small, light-to-dark green, and circular-to irregularly-shaped, water-soaked lesions [9]. These usually first appear on the lower leaves where the microclimate is more humid. Temperature and moisture are important factors for the development of the disease in planta. They determine the mode of sporangia germination, in establishing a parasitic interaction with the host, and the rate of the pathogen growth on the host tissue [15].

In moist weather the lesions enlarge rapidly and form brown, blighted areas with indefinite borders. A zone of white, downy mildewy growth 3-5 mm wide appears at the border of the lesions on the undersides of the leaves. Soon entire leaves are infected, die, and become limp [6]. The spores germinate and infect the exposed tubers. Although, some of the infected tubers get completely rotted by the time, crop is harvested but, still lot of tubers carry incipient infection, and escape in the cold store/country store where they remain dormant but alive [16].

It has spread far and wide and now occurs wherever potatoes are grown. Wind or splash borne sporangia are the primary means for spatial increase and disease which involves the removal of spores from sporangiophores by rain or irrigation water. Splash-borne sporangia are generally deposited very close to the inoculum source, and have a good chance of survival given the moisture requirements of the germination process. Most airborne sporangia are deposited with in several meters of the inoculum source, but dispersal over larger distances take place. Spore released from sporangiophores of the potato canopy, and wind and atmospheric turbulence lift spores up through the canopy making them to move long-distance [6].

However, wind and atmospheric turbulence can be affected by the time of day spore release, height of spore release, and canopy structure. The atmospheric turbulence spreads and dilutes the spore cloud, and spores are lost through gravitational settling and washed-out by rain; detached sporangia are sensitive to drying out, but mainly to DNA damage by ultraviolet radiation [17]. It can be also dispersed by farm equipment and animals. The most important is the transport of seed tubers to other growing areas and it has resulted in spatial spread of the pathogen at intercontinental scales [8].

2.4 Yield loss Caused by Potato Late Blight

Potato late blight is a very serious economic threat in the vast majority of potato production systems. Yield loss depends on availability of inoculum, susceptibility of the host, stage of plant attack, prevailing environmental condition, etc. grown. Losses due to *Phytophthora infestans* have been estimated to € 12 billion per annum, of which, the losses in developing countries have been estimated around € 10 billion per annum [18].

It attacks the leaves, stems, and tubers of potato plants. It is one of the few plant diseases that can absolutely destroy a crop, producing a 100% crop loss. The potential economic and social impact of this disease is best illustrated by the well-publicized role it played in the Irish Famine in the middle of the 19th century when it destroyed a large portion of the potato crop, either by eliminating foliage prior to the harvest or by causing massive tuber rot in storage. As a result of the famine, millions of Irish died or emigrated. Late blight may cause total destruction of all plants in a field within a week or two when weather is cool and wet. Late blight may kill the foliage and stems of potato and tomato plants at any time during the growing season. It also attacks potato tubers and tomato fruits in the field, which rot either in the field or while in storage [6].

The average global crop losses of all diseases combined was approximately 12.8% of the potential production but potato alone was subjected to 21.8% loss [19]. In the temperate regions of North America, potato late blight has caused tremendous economic impact over many years due to potato crop loss or destruction [20]. Yield losses due to late blight of potato were reported up to 50-70% during the year 2007 under favorable environmental condition in Pakistan [21]; however recently Ahmed et al. [22] reported that late blight can induce 100% yield loss under epidemic condition in Pakistan.

In Ethiopia, the disease caused 100% crop loss on unimproved local cultivar, and 67.1% on a susceptible variety [23]. Late blight is a major limitation to potato production in high humid elevations; with estimate average yield losses of about 30–75% on susceptible varieties [24]. Research centers have made estimates of losses ranging from 6.5 to 61.7%, depending on the level of susceptibility of the varieties. According to [25] and [26] report, in Ethiopia, late blight of potato causes tuber yield losses of 21.71–45.8% and 29-57% depending on the resistance level of the cultivars, respectively.

2.5 Sampling Techniques of Late Blight of Potato

Sampling of the crop was done 1 to 2 weeks after flowering (45 to 65 days old), the stage at which the crop tends to be most vulnerable to late blight epidemics [27]. Potato fields are sampled every 5 km even can be 10 to 15 km of a road system across each district during field survey. When potato fields are scouted, even outside the systematic interval, sampling would be made depending on the land size, crop population, stage of growth and topography. Incidence and severity can be taken in diagonal, zigzag or Z- shape assessment methods and 100 plants are examined from 10 samples of a field.

The same technique is used by [27] to obtain incidence of late blight by counting the number of infected plants in a sample of 20 plants from each of the four different positions of each potato field, making a total of 80 plants per plot. The positions are selected randomly excluding borders. Each plant sampled is assessed for late blight severity based on the 1-9 scale as described below.

2.6 Management Methods of Potato Late Blight

Late blight of potato can be managed sustainably by a variety of practices to reduce crop loss. The most effective, environmentally safe, and cost-effective management strategy is an integrated disease management. This includes; the use of cultural practices, resistance variety, biological control agents, chemical control and their integration.

2.6.1 Cultural control

Cultural practices are the first line of defense against late blight [9]. Cultural practices can be practices, which are usually applied for agriculture purposes not directly connected with crop protection, such as fertilization and irrigation and this may or may not have a positive or a negative side effect on disease incidence or severity. It also includes practices that are used completely for disease control, such as sanitation and flooding and practices, which are used for both agricultural purposes and for disease control, such as crop rotation, grafting and composting. Cultural practices can be applied to reduce the pathogen population; by reducing its survival, reproduction, dispersal and penetration of the pathogen. Survival of *P. infestans* to initiate epidemic can be reduced through avoidance of introducing late blight into a field by planting only disease-free seed tubers, preferably certified seed, destroying all cull and volunteer potatoes, avoid frequent or night-time overhead irrigation and good soil coverage [28].

Avoiding sources of inoculum is the most effective strategy for managing late blight. The initial sources of inoculum are likely to be infected potatoes in cull piles, infected volunteer potato plants that have survived the winter, and infected seed tubers. Late blight is controlled by eliminating cull piles and volunteer potatoes, using proper harvesting and storage practices, and applying fungicides when necessary. Therefore, it is important to keep a clean

Table 1. Field key for assessing Potato late blight (the description of symptoms is based on plants with 4 stems 10 to 12 leaves per stem)

CIP scale value	Blight (%)		Symptoms
	Mean	Limits	
1	0		No late blight observable
2	2.5	traces - <5	Late blight present. Maximum 10 lesions per plant
3	10	5 - <15	Plants look healthy, but lesions are easily seen at closer distance. Maximum foliage area affected by lesions or destroyed corresponds to no more than 20 leaflets.
4	25	15 - < 35	Late blight easily seen on most plants. About 25 % of foliage is covered with lesions or destroyed.
5	50	35 - < 65	Plot looks green; however, all plants are affected. Lower leaves are dead. About half the foliage area is destroyed.
6	75	65 - < 85	Plot looks green with brown flecks. About 75 % of each plant is affected. Leaves of the lower half of plants are destroyed.
7	90	85 - < 95	Plot neither predominantly green nor brown. Only top leaves are green. Many stems have large lesions.
8	97.5	95 - < 100	Plot is brown-colored. A few top leaves still have some green areas. Most stems have lesions or are dead.
9	100		All leaves and stems are dead

Source: [29]

operation by destroying all cull and volunteer potatoes. Seed sources should be selected carefully to avoid bringing in late blight on seed, especially new strains of the pathogen. When partially blighted leaves and stems are surviving at harvest time, it is necessary to remove the aboveground parts of potato plants or destroy them by chemical sprays (herbicides) or mechanical means to prevent the tubers from becoming infected [6].

The date of potato planting is also useful to avoid the late blight of potato, especially by changing in planting dates. Avoiding use of excess nitrogen and use of moderate nitrogen fertilization is often recommended as cultural practices to delay the development of late blight [30]. Higher dose of phosphorus and potassium has been found to give a higher yield in a late blight year [31]. Late season excessive irrigation and fertilizer applications should be limited. Carefully scheduled and minimizing the frequency of irrigation should be practiced Since wet conditions are favorable for infection, particularly late in the season when the closed potato canopy provides ideal conditions for late blight development. If possible, rows should be oriented parallel with prevailing winds to encourage better air circulation and foliage drying. Studies in Israel noted that late blight infection was greater on morning-irrigated potatoes than on potatoes irrigated at midday or evening.

It may also be beneficial to spray foliage after vine killing with labeled fungicides to kill living late blight spores on the foliage [9]. Harvest should be managed to minimize damage to tubers [32]. After harvest, if tubers are stored, they should be dry when placed in storage, and the storage air temperature and humidity should be managed. Store tubers harvested from diseased fields, separately from that of healthy fields. Potatoes should be stored dry and at the lowest temperature possible to suppress pathogen growth and spread. Scouting all stored potatoes frequently and removing diseased tubers from storage is desirable to prevent disease spread [32].

2.6.2 Host- resistance

Host resistance is the best option for management of late blight of potato and it is eco-friendly in nature. After a decade, resistant level of the cultivars is being defeated, due to matching of new virulence genes. To find out the source(s) of resistance to late blight in potato was serious concern after Irish famine, during late 19th century. In case of *P. infestans*, locating host resistance becomes more difficult as the host range is narrow. Resistance to Phytophthora species in different hosts is of non-specific nature. Invasion of host by the pathogen leads to the production of many antifungal agents such as phytoalexins. Phytoalexins provide resistance to the host against pathogen, but their inhibitory mechanisms are non-specific. They can induce physical or chemical pathways irrespective of the pathogen nature. The elevated levels of phytoalexins are reported in the presence of compounds (carbohydrates, lipids, amino acids and proteins) of pathogen origin [28].

The use of resistant varieties is among the most effective and environmentally safe means of managing the disease. Variations in resistance to late blight among different potato varieties have been demonstrated by several researchers [32]. Early-maturing varieties are usually susceptible to the disease with exception of some cultivars. Some varieties have useful foliage resistance but poor tuber-blight resistance. Yet, others have good tuber-blight resistance but poor foliage-blight resistance. Ideally, a variety should have good resistance to both foliage and tuber blight. However, no potato varieties are fully resistant to late blight [32].

Generally resistant potato varieties and improved cultural practices can reduce late blight [33]. The search for novel crop protection strategies has led the attention towards increasing plant immunity. Many crops get affected by the pathogens due to their weak immunity. Susceptible plants can be protected by stimulating defense mechanism which results in alteration of innate immunity. Systemic acquired resistance (SAR) is trigged by plants due to primary infection caused by pathogens, which aid the potential immune system in succeeding infections [34]. Systemic acquired resistance inducers such as elicitors can act as boosters of crop innate immunity and may provide a durable solution against pathogenic microbes [35].

2.6.3 Late blight management with pesticide application

Application of fungicides is the most frequently adopted control method globally. According to Beckerman [36], fungicides can only slow or stop the development of new symptoms but cannot cure existing symptoms. Therefore, its application should be before disease development. Several broad-spectrum and systemic fungicides are used for blight management. Protection by fungicides is temporary because they are subject to weathering and breakdown over time. Fungicides that are used against late blight can be classified into two basic mobility groups: protectant or penetrant. Fungicides can slow or stop the development of new symptoms if applied in a timely fashion, but fungicides will not cure existing light blight symptoms. Hence, most fungicides need to be applied before disease occurs or at the first appearance of symptoms to be effective.

Also, the damage caused by late blight on plants often does not go away, even if the pathogen is killed. Fungicides can only protect new uninfected growth from the disease. Several broad-spectrum and systemic fungicides are used against potato late blight control [36]. The new strains of the oomycete produced as recombinants of fertilization of the two mating-types (A1 and A2) are resistant to some of the systemic fungicides like, metalaxyl and, therefore, sprays with such materials are ineffective against such strains [35].

2.6.4 Biological control

Management of late blight by eco-friendly means is a difficult task particularly when the level of disease pressure is high along with prevailing congenial environmental condition. However, due to negative impact of chemicals on environment as well as human health, nowadays eco-friendly management is gaining more importance. Management of late blight through eco-friendly way, using botanicals has been initiated in European and American countries during the last years of 20^{th} century. Out of 100 species in 54 plant families tested against *P. infestans*, the leaf extracts from onions, garlic, *Malustoringo*, *Reynoutria japonica* and *Rheumcoreanum* revealed positive inhibition of mycelial growth of *P. infestans*. *Malus toringo* extracts strongly inhibited *P. infestans* and was effective in managing late blight also. The effectiveness of some antifungal compound was reported against late blight from botanicals [37].

A well-known group of microorganisms used is the luorescent *Pseudomonas* which excretes secondary metabolites including antibiotics and biosurfactants (naturally occurring surface active compounds derived from micro-organisms) that are inhibitory to plant pathogens [38]. The antagonist *Bacillus subtilis* B5 is also found effective in inhibiting the growth of *P.infestans* [39]. Thus, the best antagonistic activity against *P. infestans* is observed in the genera of *Pseudomonas* and *Bacillus* as they produce wide range of antibiotics and biosurfactants and can be used as alternatives to chemical surfactants [40]. Wang et al. [41] on the other hand, reported the fungus *Purpureocillium lilacinum* as an efficient and effective biocontrol agent against plant pathogens including Phytophthora.

2.6.5 Integrated disease management

Integrated management must be adopted by all producers, including large and small-scale farmers for effective control of late blight. Fungicides cannot be used alone, but must be used as one tool in an integrated management strategy. Cultural practices are the first line of defense, and forecasting techniques and proper application technology are essential for efficient, targeted applications of fungicides. The integration (combination) of moderately resistant varieties and reduced rate of metalaxyl 8% + mancozeb 64% WP application was resulted in lowering incidence of late blight of potato at 59 days after planting of disease assessment [42]. In Ethiopia, integrated disease management of late blight has been adopted as a strategy for the past 10 years. It includes host resistance in combination with cultural practices such as early planting dates and reduced dose and rate of fungicide use.

3. CONCLUSIONS

Late blight of potato caused by *Phytophtora infestans* is the most important fungal disease which threaten humans for their food security globally. The pathogen is an obligate parasite which can be reproduced both sexually and asexually. It is polycyclic disease and can complete its life cycle within a week during asexual reproduction and reproduced sexually by two opposite mating types (A1 and A2) to produce off springs and meiosis occurred. 21.8% potato crop yield is lost due to diseases and potato late blight is the major one which resulted in a yield loss ranged from 5-100 % unless it is managed appropriately. In terms of economic perspective, it causes two-digit billion dollar per annum.

In late blight of potato management, field assessment after flowering (45 to 65 days old) is highly crucial. Effective control can be performed through the integration of all strategies. Cultural practices (adjusting sowing date and use clean seed), use of host plant resistance, application of several broad-spectrum and systemic fungicides (metalaxyl and mancozeb), and use of *Pseudomonas* and *Bacillus* as biological control agent are the major management strategies. In general, this disease is the most series and widely distributed, causes huge economic loss globally and managed in the better way by integrated management approach.

4. RECOMMENDATIONS

The review shows that as late blight of potato is the most serious fungal disease by which potato crop loss can be as high as 100% and it highly damages the livelihood of its growers in terms of food security, cost of control of the disease and other economic losses. Although the disease is polycyclic and can cause huge loss, it can be managed through various strategies. Therefore, integrated disease management is recommended to combat the problem as best management approach.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Son SW, Kim HY, Choi GJ, Lim HK, Jang KS, Lee SO, Sung ND, Kim JC. Bikaverin and fusaric acid from Fusarium oxysporum show anti oomycete activity against P. infestans. J. of Applied Microbiology. 2008; 104:692-698.
2. Latijnhouwers M, Ligterink W, Vleeshouwers VG, VanWest P, Govers F. A Galpha subunit controls zoospore mobility and virulence in the potato late blight pathogen Phytophthora infestans. Mol Microbiol. 2004; 51:925-936.
3. LR Cooke, HTAM Schepers, A Hermansen, RA Bain, NJ Bradshaw, F Ritchie, DS Shaw, A Evenhuis, GJT Kessel, JGN Wander, B Andersson, JG Hansen, A Hannukkala, R Naerstad, BJ Nielsen. Epidemiology and Integrated Control of Potato Late Blight in Europe. Potato research. 2011; 54: 183-222.
4. Binyam Tsedaley. Late blight of potato (Phytophthora infestans) Biology, Economic Importance and its Management Approaches. Journal of Biology, Agriculture and Healthcare. 2014;4(25):215-225.
5. Fry WE, Goodwin SB, Dyer AT, Matuszak JM, Drenth A, Tooley PW, Sujkowski, LS, Koh YJ, Cohen BA, Spielman LJ, Deahl KL, Inglis DA, Sandlan KP. Historical and recent migrations of Phytophthora infestans: Chronology, pathways, and implications. Plant Disease. 1993; 77:653-661.
6. Agrios GN. Plant Pathology. 5th Edition, Academic press, London; 2005.
7. Lal M, Sharma S, Yadav S, Kumar S. Management of Potato late blight. Department of Plant Pathology, Bihar Agricultural University, Bihar, India. 2018;180.
8. Skelsey P. Multi-scale modeling of Potato late blight epidemics. PhD thesis, Wageningen University, the Netherlands. 2008;257.
9. Kirk W, Wharton P, Hammerschmidt R, Abu-el Samen F, Douches D. Late Blight. Michigan State University Extension Bulletin E-2945; 2013.
10. Judelson HS, Blanco FA. The spores of Phytophthora: Weapons of the plant destroyer. Microbiology. 2005; 3:47–58.
11. Turkensteen LJ, Flier WG, Wanningen R, Mulder A. Production, survival and infectivity of oospores of Phytophthora infestans. Plant Pathol. 2000; 49:688–696.
12. Dey TK, Hossain M, Kadian MS, Hossain S, Bonierbale M, Mahmud AA. Prevalence, epidemiology and management of potato late blight in Bangladesh. Potato Journal. 2010;37(3–4):99–102.
13. Chindi A, Giorgis GW, Solomon A, Tessama L, Negash K. Rapid Multiplication Techniques (RMTs): A Tool for the Production of Quality Seed Potato (*Solanum tuberosum* L.) in Ethiopia. Asian J. Crop Sci. 2014; 6:176–185.
14. Lal M. Fungal foliar diseases of potato and their management (Course on disease and pest management in potato complied and produced by Sanjeev Sharma, Vinay Sagar, Ravinder Kumar, Sridhar Jandrajupalli, Dhiraj Kumar Singh) published by ICAR-CPRI Shimla. 2016;22-27.
15. Becktell MC, Daughtrey ML, Fry WE. Temperature and leaf wetness requirements for pathogen establishment, incubation period, and sporulation of phytophthora infestans on petunia x hybrida. Plant Dis. 2005; 89:975-979.
16. Sharma S, Sundaresh S, Singh BP. Late blight of potato. In: BP singh, M Nagesh, Sanjeev Sharma, Vinay Sagar, A Jeevvlatha and J Sridhar, editors. A manual on diseases and pest of potato-Technical Bulletin No. 101 ICAR-central potato research institute, Shimla, HP, India. 2015;1-6.
17. Mizubuti ESG, Aylor DE, Fry WE. Survival of Phytophthora infestans sporangia exposed to solar radiation. Phytopathology. 2000; 90:78-84.
18. Haverkort AJ, Struik PC, Visser RGF, Jacobsen E. Applied biotechnology to control late blight in potato caused by Phytophthora infestans. Potato Res. 2009; 52:249-64.
19. Ephrem Guchi. Disease Management Practice on Potato (*Solanum tuberosum* L.) in Ethiopia. World Journal of Agricultural Research. 2015; 3:34-42.
20. Guenthner JF, Michael KC, Nolte P. The economic impact of potato late blight on US growers. Potato Resource. 2001; 44:121–125.
21. Haq I, Rashid A, Khan SA. Relative efficacy of various fungicides, chemicals and biochemicals against late blight of potato, Pakistan. Journal of Phytopathology. 2008; 21:129-133.
22. Ahmed N, Khan MA, Khan NA, Ali MA. Prediction of potato late blight disease based upon environmental factors in Faisalabad. J. of Plant Pathol. and Microbiol. 2015; 3:1-6.

23. Bekele Kassa, Yaynu Hiskias. Tuber yield loss assessment of potato cultivars with different levels of resistance to late blight. In: "Proceedings of the 3rd Annual Conference, of Crop Protection Society of Ethiopia. (Eshetu Bekele, Abdurahman Abdulahi, Aynekulu Yemane. eds.), CPSE, Addis Abeba, Ethiopia. 1996;149-152.
24. Olanya OM, Adipala E, Hakiza JJ, Kedera JC, Ojiambo P, Mukalazi JM, Forbes G, Nelson R. Epidemiology and population dynamics of Phytophthora infestans in Sub-Saharan Africa: Progress and Constraints. African Crop Science Journal. 2001; 9:181-193.
25. Fekede Girma, Amare Ayalew, Nigussie Dechassa. Management of Late Blight (Phytophthora infestans) of Potato (*Solanum tuberosum*) through Potato cultivars and Fungicides in Hararghe Highlands, Ethiopia. International Journal of Life Sciences. 2013;2(3):130-138.
26. Binyam Tsedaley, Temam Hussen and Tekalign Tsegaw. Tuber yield loss assessment of potato (*Solanum tuberosum* L.) varieties due to late blight (Phytophthora infestans) and its management Haramaya, Eastern Ethiopia. Journal of Biology, Agriculture and Healthcare. 2014b;4(23):45-54.
27. Mukalazi J, Adipala E, Sengooba T, Hakiza JJ, Olanya M, Kidanemariam HM. Variability in potato late blight severity and its Effect on Tuber Yield in Uganda. African Crop Science Journal. 2001;9(1):195-201.
28. Umesh Goutam, Kajal Thakur, Neha Salaria, Sarvjeet Kukreja. Recent Approaches for Late Blight Disease Management of Potato Caused by Phytophthora infestans. P. Gehlot, J. Singh (eds.), Fungi and their Role in Sustainable Development: Current Perspectives. Springer Nature Singapore Pte Ltd. 2018; 311- 325.
29. Jan W Henfling. Late Blight of Potato. Second edition. International potato center, Lima Peru. 1987; 25.
30. Arora RK, Shrama S, Singh BP. Late blight disease of potato and its management. Potato Journal. 2014; 41:16-40.
31. Roy SK, Sharma RC, Trehan SP. Integrated nutrient management by using farmyard manure and fertilizers in potato-sun lower-paddy rice rotation in the Punjab. The Journal of Agricultural Science. 2001; 137:271-278.
32. Tsedaley B. Late Blight of Potato (Phytophthora infestans) Biology, Economic Importance and its Management Approaches. Journal of Biology. 2014;4(25):215–226.
33. FAO (Food and Agriculture Organization). Potato World: Africa-International Year of the Potato 2008. Rome; 2008.
34. Oostendorp M, Kuntz W, Dietrich B, Staub T. Induced disease resistance in plants by chemicals. Eur J. Plant Pathol. 2001; 107:19–28.
35. Bektas Y, Eulgem T. Synthetic plant defense elicitors. Front. Plant Sci. 2015; 5:1-17.
36. Beckerman J. Fungicide resistance management. Oklahoma Cooperative Extension Service Purdue Extension. Oklahoma; 2008.
37. Khan MA, Singh BP, Kaushik SK, Lal M. Evaluation of antifungal potential extracts against potato pathogens. National Seminar on emerging problems of potato, CPRI Shimla. 2014;143.
38. Haas D, Defago G. Biological control of soil-borne pathogens by luorescent pseudomonads. Nature Reviews. Microbiology. 2005; 3: 307-319.
39. Ajay S, Sunaina V. Direct inhibition of Phytophthora infestans, the causal organism of late blight of potato by Bacillus antagonist. Potato J. 2005; 32:179-180.
40. Banat IM, Makkar RS, Cameotra SS. Potential commercial application of microbial surfactants. Applied Microbiology and Biotechnology. 2000; 53:495-508.
41. Wang G, Liu Z, Lin R, Li E, Mao Z, Ling J, Yang Y, Yin WB, Xie B. Biosynthesis of antibiotic Leucin statins in bio-control fungus Purpureocillium lilacinum and their inhibition on Phytophthora revealed by genome mining. PLoS Pathog. 2016;12(7):1-30.
42. Binyam Tsedaley, Temam Hussen, Tekalign Tsegaw. Tuber yield loss assessment of potato (*Solanum tuberosum* L.) varieties due to late blight (Phytophthora infestans) and its management Haramaya, Eastern Ethiopia. J. Biol. Agric. Healthc. 2014a; 4:45–54.