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Efficacy of different eco-friendly methods against late blight of potato, *Phytophthora infestans*: A review

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Abstract
One of the most dramatic episodes induced by a plant pathogen in human history was the late blight of the potato caused by the fungus *Phytophthora infestans*, which was responsible for the famine in Ireland (1845). Famine in Ireland claimed the lives of one million people. Therefore, it is essential to achieve eco-friendly methods potato late blight disease management. Due to the rapid spread of late blight outbreaks in recent years, management efforts have solely focused on the application of fungicides. Fungicide use, however, poses a major risk to both the environment and public health when used carelessly. Additionally, it causes the pathogen to develop a resistance and has a negative impact on helpful species including nitrogen fixers, resident antagonists and mycorrhizal fungi. Therefore, environmentally friendly methods for managing late blight are needed as a top priority in order to reduce the usage of fungicides. Most recently, Late blight fungal isolates have undergone considerable modifications, including variations in how aggressive they are toward the crop. Since late blight affects the entire community, all producers, farmers, gardeners and growers must implement an efficient, environmentally friendly management strategy with the assistance of governmental organizations, extension specialists, crop consultants, *etc.* The first line of defense in this situation is disease management through cultural practices and the efficient, effective and environmentally friendly management of late blight of potatoes depends on forecasting system, physiological strategies, biological control, host plant resistance and bio-technological approach.

Keywords: *Phytophthora infestans,* pathogen, biological control, antagonists and eco-friendly

1. Introduction

Late blight caused by the oomycete pathogen *Phytophthora infestans*, disease of major concern all over the world is costing huge losses every year in potato (Kumaon *et al*., 2009) [84]. Reports of complete field destruction due to late blight epidemics are relatively common. The fungus is responsible for global annual crop loss of US $ 12 billion. Yield loss due to late blight in India varies from year to year and range from 20 to 75% (Sundaresha *et al*., 2015) [145]. The pathogen *Phytophthora infestans* is highly variable and has sophisticated weaponry including effectors molecules coded by avirulence genes that allow rapid infection and host tissue colonization (Kamoun and Smart, 2005) [85]. Once inside host tissue, a complex set of compounds such as metallopeptidase, cutinase and other protein with no identification function required for cell killing and nutrient uptake are promptly activated (Lee *et al*., 2006) [100]. There are ten avirulence proteins are known to be involved in pathogenesis and act as effectors that are delivered inside the plant cell (Haldar *et al*., 2006) [72]. These protease inhibitors produce by the pathogen to disturb the defense mechanism of the host plant. New class of protease inhibitors were described in *Phytophthora infestans* (Tian *et al*., 2007) [147]. For more than a decade, controlling late blight has become increasingly demanding because of the emergence of new strains of the pathogen, some new strains are known to be more aggressive and resistant to the fungicide metalaxyl (Daayf *et al*., 2001) [38]. Moreover, indiscriminate use of systemic fungicides especially metalaxyl (ridomil) provides chance to develop resistant strain of the fungus has been reported from home and abroad (Singh, 2000) [138]. The term alternative can have multiple meanings and its interpretation varies accordingly. In this context, Cultural control is the first line of defense which includes change in date of planting, intercropping, nutrient management, irrigation management *etc.* For eco-friendly disease management, forecasting system plays important role so that preventive measures can be taken up if there is likelihood of disease appearance. In the last decades, growers and researchers have made impressive strides in implementing successful local epidemic forecasting systems and guided chemical pesticide management regimes for efficient PLB control in the field (Poudel *et al*. 2020) [115]. Physiological strategies *i.e.* escape and resistance is very important to cope up with disease. In general, due to the different modes of actions (*i.e.* antagonistic effects or induction of plant defense mechanisms), the use of microorganisms as biological control agents has a definite potential. Currently potato varieties with fully late blight resistance are under serious study in breeding programme. A new sexually reproducing potato late blight (*Phytophthora infestans*) population characterised by early oospore-derived epidemics is one of the most severe threats to organic potato production (Lehtinen and Hannukkala, 2004) [101]. In some growth areas, up to eight pesticide applications per growth season is required for sufficient control, presenting both heavy economic and environmental costs associated with potato production (Naumann *et al.,* 2020) [108]. Innovative and effective control measures are needed if fungicide use is to be reduced or eliminated as in case of organic potato production. These so-called effector molecules could function either within or outside of host plant cells, participating in diverse physiological processes such as nutrient uptake, plant cell wall degradation and host defense signaling interference (He *et al*. 2018; Du *et al.* 2021) [75, 44]. Protectants are capable of preventing *P. infestans* infection by interfering with spore germination and/or initial penetration of plant surface processes (Lamichhane *et al*. 2018) [98].

This technology has been recently applied to clone *R* genes from wild wheat species (Arora *et al.* 2019) [10], as well as genome-wide curation of *R* genes across 18 *Solanum* species (Seong *et al.* 2020) [121] and diverse *A. thaliana* accessions (Van de Weyer *et al.* 2019) [153].

Thus, they may represent an interesting tool for the development of novel concepts in disease management. Even biotechnology is also being employed in the pursuit of late blight resistance. Fully resistant genetically engineered strains are expected soon. In this review, we will try to use eco-friendly approaches that include non-fungicidal strategies such as cultural method, forecasting system, physiological strategies, biological control, host plant resistance and bio-technological approach for management of late blight disease.

2. Pathogen

In 1861, Anton de Bary experimentally established that the fungus was the cause of plant dis- ease known as late blight of potato, a disease that closely resembles the downy mildew. In 1875, de Bary studied it in detail and gave name the pathogen to *Phy- tophthora infestans* which means infectious plant destroyer (Turner, 2005; Widmark, 2010) [151, 164]. Phytophthora belongs to the kingdom Stramenopila, a group of micro-organism that is closely related to brown algae, golden brown algae and diatoms. This statement supported the references (Forster *et al*., 1990; Dick, 2001;Kamoun and Nusbaum, 2009;De Bary, 1876; Widmark, 2010) [54, 43, 84, 40, 164]. Anton de Bery also showed that late disease could easily appear on fungal spore dusted on potato plants.

2.1 Pathogen variability

Important aspects of monitoring population structure of *Phytophthora infestans* should be considered for thorough analysis and proper development of alternative procedures aiming at controlling the late blight in potato. Even it has been on the agenda of scientific community and techniques have become available. Biological markers including mating types, race pattern, metalaxyl sensitivity and ploidy are the potential means for monitoring variability in *Phytophthora infestans.* The occurrence of sexual reproduction also affects the population dynamics of the pathogen. Two contrasting scenarios for genetic structure of population of *Phytophthora infestans* can be envisioned: (1) A clonal population structure with limited number of clonal lineages (Eduardo *et al*., 2007) [47]. High genotypic diversity of pathogen can provide greater potential for local adaptation to the changing environment which makes disease management more difficult (Sujkowski *et al*., 1994) [144]. (2) A panmictic population is comprised of a large number of distinct genotypes of *P. infestans***.** In areas where population is clonal, the risk of new diversity being introduced grows as seed trade becomes more globalized.

2.2 Physiological races

Fungus *Phytophthora infestans* is consider as highly variable due to the frequent appearance of its new pathogenic virulent types in field and often observed in the laboratory. Giddings and Berg, 1919; Berg, 1926) [65, 14] were pioneers in detecting variations in the *Phytophthora infestans* populations. After almost seven years of introduction of resistant hybrids/cultivars having R genes, pathological specializations (races) within potato isolates were reported by Schick (1932) [120]. In 1958, race 0 and race 1 were prevalent, the former being predominant in North-western hills. In 1965, race 3 and 4 appeared for first time (Dutt, 1965) [46]. In 1969, race 0 was still common race (58%) but frequency of race 1 increased considerably (42%) over the years. Two gene complex races recorded in 1971 attacked the late blight resistant varieties *i.e.* Kufri Jyoti, K. Jeeevan (Phadtare *et al*., 1973) [113]. Thirteen new races were identified by 1975 in Shimla hills. By 1978, the complex races started appearing more frequently. Absence of race 0 and predominance of race 3, 4, 7, 8, 10, 11 indicated the shift in the virulence of *Phytophthora infestans* was almost complete. This statement supported the references (Bhattacharyya and Singh, 1986; CPRI, 1981 and 1987; Rivera-Pena, 1995; Cristinzio *et al*., 1998;CPRI, 2013;CPRI, 1999; Shanmugam, 2001) [15, 30 31, 117, 35, 33, 127]. However, universal appearance of races or, at least their detection, did not occur until resistance genes from *Solanum demissum* were transferred to commercial potato species, *S. tuberosum*. Since then, race spectrum in different countries/regions has been monitored regularly. Virulence to all major resistance genes was recorded (Guo *et al*., 2009) [68].

2.3 Mating types

Phytophthora infestans is heterothallic and requires two mating types for sexual reproduction. Prior to 1984 the A2 mating type was restricted to Mexico and Andean mountains. Singh *et al*., (1994) [136] reported the presence of A2 mating type in India. Occurrence of A2 mating type in different parts of the world is considered to be due to a second migration of *Phytophthora infestans* from Mexico (Fry *et al*., 1999) [58], the first being from Europe and America during the historical potato famine around the year 1845. In India, A2 mating type has stabilized in temperate hills while the A1 is dominating in sub-tropical plains (Singh *et al*., 2005; CPRI, 2013) [137, 33]. Oospores germinate by means of a germ tube that produces a sporangium, although at times the germ tube grows directly into the mycelium. Sporangia germinate almost entirely by releasing three to eight zoospores at temperatures up to 12 or

15 °C, whereas above 15 °C temperature, sporangia may germinate directly by producing a germ tube (Agrios, 2005) [2]. The new strains of the pathogen have been found to be more aggressive than the old population (Fry *et al*., 1999) [99]. First report of A2 mating type outside Mexico was from Switzerland (Hohl and Iselin, 1984) [77]. Subsequently, A2 mating type was detected in other countries too. When the two mating types grow adjacently, the female hypha grows through the young antheridium (male reproductive cell) and develops into a globose oogonium (female reproductive cell) above the antheridium. The antheridium then fertilizes the oogonium, which develops into a thick walled and hardy oospore (Tsedaley, 2014) [150]. Recent work has indicated that the new *Phytophthora infestans* clones, especially the US-8 and US-14 genotypes, are more aggressive (Kirk *et al*., 2009) [95]. Migration and sexual recombination can play an important role in enhancing genetic diversity in *P. infestans*. An increasing severity of late blight, a shift in pathogen population toward increased specific viru- lence and an increased tolerance to metalaxyl has been recorded in past three decades in the north western plains of India (Arora, 2008) [9].

2.4 Metalaxyl resistance

Metalaxyl, a phenylamide group of systemic fungicide, acts by interference in RNA synthesis by inhibition of rRNA polymerase or both RNA and DNA synthesis. Due to its site specific nature, it becomes more prone to development of resistance in the pathogen. Fungicide resistant isolates were detected in oomycetous fungi soon after the introduction of these fungicides as single products on various crops including *Phytophthora infestans* in Europe, the Middle East and in the Moscow region at the end of 1980. In India, resistance to metalaxyl in *Phytophthora infestans* wild population was first observed in Nilgiri hills of South India in 1989.

Metalaxyl resistant strains appeared towards the end of summer crop season and their frequency increased to 13 per cent in autumn season. Since then the monitoring for met- alaxyl resistance is being done regularly. A few strategies have been identified to manage the problem of resistance against metalaxyl in *Phytophthora infestans*. These include withdrawal of straight product and introduction of mixture with contact residual fungicides, regulation of number of sprays and their use early in the season *etc.* This statement supported the references (Arora *et al*, 2014; Arora *et al*., 1992) [8, 7].

2.5 Disease symptoms

Disease symptoms are characterized as circular or irregular water soaked lesions on leaves. Initially, these lesions are localized on tips and margins of the leaves, sometimes surrounded by pale yellowish border. Lesions develop very fast into brown to black necrotic spots and cover entire leaf surface. These lesions also appear on the stem. Whole crop gives blighted appearance and may destroy under high disease severity. Under favourable weather condition (cool and high wetness period) white, fluffy fungal growth may be visible primarily on the underside of the leaf which is the main distinguishing feature of late blight disease. These lesions in affected tubers spread irregularly from the outer surface (3 mm) to deep (10 mm) in pulp. Disease appears on stem as grayish brown to black elongated lesions. Under high moisture and low temperature conditions, it sporulate profusely and destroy entire green top of the plant. Fry *et al*., (2001) [59] also recorded reddish brown, dry, hard and granular lesions in potato tubers.

2.6 Epidemiology

Infected seed tubers put into cold storage are responsible for perpetuation of fungal spores and mycelial growth from one season to another. 0.01% to 3.0% of tuber infection is sufficient to initiate and develop late blight epidemic in the next cropping season (Bhattacharyya *et al*., 1990). Congenial conditions for appearance and build up of late blight disease includes 18^0 to 22 °C temperature and 80 to 100% RH (Fry *et al*., 2001) [59]. Production of sporangia and their germination are an important key stages in the life cycle of pathogen which lead to infection, are mainly dependent on high humidity so humidity is always consider as key factor for development of disease. High relative humidity or free moisture is very important for prolonged survival of sporangia. Sporangia germinated by single germ tube at low temperature (13^0 to 21 °C) and at high temperature (30 °C) fungus slow down or stop the growth in the field. Forbes and Landeo (2006) [51] also reported that several wild solanaceous plants carry the pathogen *Phytophthora in-festans*. Ideal condition for late blight infection and development are night temperature 10-16 °C with light rain, fog, next day temperature ranged from 13 °C to 16 °C with high relative humidity (Kirk, 2009; Kirk *et al.*, 2013) [94, 93]. According to Agrios (2005) [2] at high relative humidity (near 100% RH) fungus restarts the sporulation. The fungal spores are carried by air currents and rain from infected plant to healthy plants and disease cycle restarts. Several workers also reported that the pathogen *Phytophthora infestans* has been carried into field by air currents (Martin *et al*., 1994; Kirk *et al*., 2013; Tsedaley, 2014) [106, 93, 150]. Whenever sporangia come in contact with tuber right from tuberization till harvesting, potato tubers may get infected. Generally, infection takes place when sporangia washed and fall down from lesion to soil and then through soil to tubers. During tuber enlargement period, contact between tubers and sporangia may be more because it develop cracks in the soil and sporangia become readily accessible and infection can be noticed on developing on mature tubers. Temperatures more than 18 °C suppress the infection in tubers. Fry (1998) [61] observed that sporangia can survive for a weeks or few days in soil so tuber may infected for some period of time even after infection are no longer producing sporangia. The fungus can survive in living tissues, infect- ed seed tubers, infected tubers in cull piles, unharvested and volunteer potatoes left in the ground (Shinners *et al*., 2009; Kirk *et al*., 2013) [130, 93]. Wind, splashed rain, mechanical transport and animals etc are responsible for spread of sporangia from one field to another produced by fungus *Phytophthora infestans* (Martin *et al*., 1994; Kirk *et al*, 2013) [106, 93]. After few days of infection, new sporangiophore emerges from stomata of leaves and gives rise to numerous sporangia. Sporangia germinate either directly by germ tube or indirectly by liberating zoospores. Germ tube enters through stomata and mycelium grows between the cell and send long curled haustoria into the cell. Agrios (2005) [2] concluded that as disease develop under favourable condition, the already established lesions increase in size and cover the entire surface of leaves, new ones lesion also develop, kill the foliage and finally reduce the tuber yield. During wet weather when sporangia washed away from leaves and reached into the soil, the second phase of disease starts in the field. Zoospores develop and penetrate the tubers through wounds, mechanical injury or through lenticels. Mycelium grows profusely between the cells and send haustoria into the cells of tubers. During harvesting, tubers got contaminated due to presence of living sporangia in the soil or on diseased foliage and become infected. The excessive humidity (near 100%) coupled with suitable temperature ranged from 15 °C to 25 °C important for disease development (Agrios, 2005) [2]. Generally. pathogen survives in infected tubers in areas where sexual repro- duction does not take place. According to Fernandez- Pavia *et al*., (2004) [49] fungus may survive in soil for many years in areas where viable oospore or sexual reproduction occurs and supported the other (Tiwari *et al.*, 2021) [148].

2.7 Disease management

The main obstacle associated with late blight management is emergence of new strain of *Phytophthora infestans* which always create a major challenge to potato growers. So management of late blight disease through integration of several options *i.e.* cultural control, disease forecasting system, physiological strategies, biological control, host plant resistance and bio-technological approaches can help to overcome this major challenge by avoiding environmental hazards by fungicides.

2.7.1 Cultural control

Garrett and Dendy, (2001) [63] observed that reduction in pathogen populations by lower down the survival, dispersal and reproduction of pathogen are main principle of cultural control which can be achieve by change in date of planting, intercropping, nutrient management and irrigation management.

2.7.1.1 Change in date of planting

Change in normal planting time not only gave maximum tuber yield but also reduced 10-15% late blight disease (Deshraj *et al*., 1997; Garg *et al*., 1999;Shailbala and Pundhir, 2006) [42, 62, 122] less late blight disease incidence were noticed in early planted crop. This may be due to significantly higher population of phylloplane fungi in early planted crop and showed less disease pressure (Shailbala and Pundhir, 2007) [123]. Change in planting date affect the crop susceptibility towards disease and its potential to attack and infect adjacent crops (Hospers-Brands *et al*., 2008) [78].

2.7.1.2 Intercropping

Intercropping of potato with garlic crop in 1:3 ratio gave the best results for management of late blight of potato crop and become as potential intercropped crop due to chemical secreted from root of the garlic affect the late blight disease Kassa and Sommartya, (2006) [86]. Shailbala and Pundhir, (2007) [123] reported that intercropping of potato cultivar Kufri Chipsona with mustard cultivar Divya showed less disease incidence, less infection rate, high tuber yield and finally more return. Bouws and Finckh (2008) [21] concluded that potato intercropped with cereals and clover grass may reduce the late blight disease pressure.

2.7.1.3 Nutrient management

To get high tuber yield and quality tubers, nutrient dose in balanced proportion is primary requirement for potato crop (Imas and Bansal, 1999) [79]. Always avoid excessive use of nitrogen to the potato crop produce lush green, large canopy which maintain excessive moisture in between the crop and increase the risk of late blight disease. Even make crop more susceptible to infection. Marschner, (1995) [105] reported that optimum dose of potassium fertilizer lower down the late blight incidence.

2.7.1.4 Irrigation management

Potato tubers are sown in ridges to avoid the contact of potato tubers to excessive moisture which may lead to rotting *etc.* Irrigation plays very important role to manage the late blight disease. If soil moisture is more than field capacity for at least 24 hours followed by ≥ 8 mm rainfall results tuber infection by pathogen *Phytophthora infestans* (Adams and Stevensen, 1990) [1]. To minimize the duration of leaf wetness, irrigation management is very important. During morning hours foliage become wet due to presence of dew. Irrigate the crop during morning hours so that irrigation coincides with leaf wetness period just because of dew. Alternatively irrigate the crop during day time because foliage goes through drying period. Very long wetness period is responsible to increase late blight risk. If possible drip irrigation can also be practiced to minimize irrigation applied leaf wetness.

2.7.2 Disease forecasting system

More precise and timely environmental monitoring, weather forecasting, technology transfer network at state, zonal and national level are main factors for disease forecasting. Different late blight forecasting models utilized in many potato growing areas of world which adequately and efficiently forecast the first appearance of disease in particular area. Late blight forecasting models are area specific due to variation in weather condition. Van Everdingen, 1926; Bourke, 1953) [154, 19] developed Irish rules for Irish peoples to forecast the disease and concluded that atleast 12 hours of wetness period, air temperature not less than 10 °C and 90% RH are required by sporangia of *Phytophthora infestans* for germination and infection. Temperature, dew period, cloudiness and rainfall were used to predict initial appearance of late blight disease in Holland. According to Smith (1956) [139], minimum temperature 10 °C for two consecutive days and at least 11 hours of RH ≥ 90% is favourable for disease development. Accurate forecasting can be possible to those diseases which are sporodic in nature (Bourke, 1970; Keane, 1995) [20, 88]. Daily maximum temperature 17^0 to 24 °C, minimum temperature ≥ 10 °C , RH at noon ≥ 75%, daily rainfall ≥ 0.1 mm are important factor to assess the risk of potato late blight disease (Forsund, 1983) [55]. Henshall *et al.*, (2006) [76] developed Shtienberg model for late blight risk in which they combined inoculum index with infection index to develop 0 to 3 late blight risk index corresponding to nil (0), light (1), moderate (2) and severe (3) risk of disease. Sharma (2000) [128] developed late blight forecasting model for North Western region of India especially Jalandhar and concluded that disease development was positively correlated with maximum RH, rainfall, dew and cloudy days.

2.7.2.1 Favourable days model

Daily rainfall, maximum and minimum temperature are important features of favourable days model. For different potato growing areas, thermohydrograph were prepared by Dutt (1964) [45] which indicate blight periods of that particular area. Singh *et al*., (2000) [135] developed, a computerized forecasting system known as Jhulsacast against late blight of potato for Western U.P. for rainy as well as non-rainy years, in which model 1 for rainy year includes measurable rain (0.1-0.5 mm) for a minimum of 2 consecutive days, 5 day moving >85% relative humidity period ≥ 50 hours and 5 day moving congenial temperature (7.2-26.6 °C) period ≥ 120 hours while model 2 for non-rainy year includes 7 day moving >85% relative humidity period ≥ 60 hours and 7 day moving congenial temperature (7.2-26.6 °C) period ≥ 120 hours. If 7 days moving precipitation average 30 mm for Shimla, 28.9 mm for Ooctamound and 38.5 mm for Shillong with mean temperature ≤ 23.9 °C for 7 consecutive days or hourly temperature ranged from 10^0 – 20 °C with ≥ 80% RH for 18 hours for two consecutive days, late blight would appear within 3 weeks (Bhattacharya *et al*., 1983) [16].

2.7.2.2 Severity value model

The first appearance of late blight and periods of late blight favorable weather can be predicted using relative humidity, rainfall and temperature data collected from an electronic weather monitor or a hygrothermograph. The weather data is converted into units called severity values (SV) for the purpose of predicting late blight outbreaks. Late blight is first expected to appear within 12 weeks after 18 SV have accumulated. Fungicide applications to protect potatoes should be initiated as soon as possible after 18 SV have accumulated. The Wallin system was developed by Wallin JR (1962) [161] in Midwestern United States which interprets the epidemiologic conse- quences of extended periods of high relative humidity and temperature during those humid periods. Late blight is forecast to occur 7 to 14 days after 18 severity value have accumulated.

2.7.2.3 Negative prognosis model

Ullrich and Schrodter (1966) [152] gave negative prognosis model uses measurement of temperature, relative humidity and rainfall to predict when late blight epidemics are not likely to occur. It has been used to predict the timing of the first prophylactic treatment in Germany. Daily and accumulated risk values over a week are calculated starting at crop emergence. Disease is expected when accumulated risk value has exceeded the threshold of 150.

2.7.2.4 Model with spatial dynamics

Minogue and Fry (1983) [107] modelled the spatial dynamics of potato late blight and found that blight foci expand with constant velocity determined by host resistance and fungicide use. Ferrandino, 1989;Paysour and Fry, 1983) [50, 112] used a model to calculate the level of inter plot interference in experiment with potato late blight.

2.7.2.4.1 Mathematical model on late blight disease

Johnson *et al.*, (1996) [82] developed two discriminant function and two logistic regression models to forecast outbreak of late blight in South Central area of Washington State. The first discriminant function uses the following variables: late blight out break during the preceding year (Y_p=0=no; Y_p= 1= yes), number of days with rains greater than or equal to 0.25 mm during the month of April and May and total precipitation during May when daily minimum temperature was more or equal to 5 °C (P_m). The second discriminant function uses Y_p, R_{am} and number of days with rain more or equal to 0.25 mm during July and August.

2.7.2.4.2 Simulation model

Waggoner, (1968) [160] presented the first computer simulation model for potato late blight in which the effect of environmental condition on the resistance component was extensively modelled. A procedure for timely fungicide application to suppress potato late blight was developed by using two simulation models. The first model stimulated the effect of environment, fungicide and host resistance on *Phytophthora infestans* in potato foliage (Bruhn and Fry, 1981; Bruhn and Fry, 1982 a, b) [22, 23, 24]. Fry *et al*. (1983) [56] described forecasting model which was derived from two simulation model. One model described weather effects on fungicide distribution and amount while second model described effects of host resistance and weather on development of *Phytophthora infestans*. Van Oijen, (1992) [155] used simulation model to evaluate the importance of different host resistance components. Andrare Piedra *et al.*, (2005) [6] discovered the domain over which a validated model may be properly used, was illustrated with lateblight, a mathematical model that stimulates the effect of weather, host growth, resistance and fungicide use on asexual development and growth of *Phytophthora infestans* on potato foliage. Forbes *et al*., (2008) [52] developed most recent version LB2004 which has been validated in the high- lands tropics and several other countries.

2.7.3 Decision support system/expert system

Decision support system increases the efficacy of control strategies without increasing disease risk in potato plant. Krause and colleagues at Pennsylvania State University (Krause *et al*., 1975) [96] developed a computerized forecast model known as BLITECAST. PhytoPRE is a computer based information and decision support system for potato late blight in Switzerland which con- sists of an epidemiological forecast model, a set of decision rules and an information system (Forrer *et al*., 1993) [53]. PROGEB forecasting model have PHYTEB as one of their components which forecasts *Phytophthora infestans* and stimulates symptomatic stages of the host (latent period, preinfection, number of infection, amount of dead tissue). PHYTEB consist of two sub models SIM- PHYT-1 and SIMPHYT-2 and forecast the beginning of epidemic 7-10 days ahead (Gutsche, 1993) [70]. Wharton *et al.*, (2008) [163] developed a web-based expert system to help potato growers in Michigan regarding control measures to mitigate the risk of potato late blight disease development. Fry *et al.*, (2015) [57] also discussed the BlightPro, a decision support system developed to aid the management of potato late blight in USA. For Indian condition Indoblightcast were developed for managing the disease in a cost effective and environmental friendly manner (Govindakrishnan *et al*., 2015) [67]. SIM- BLIGHT 1 model had been developed which requires temperature, relative humidity, information on soil moisture, crop prevalence and cultivar susceptibility (Benno kleinhenz *et al*., 2007) [13].

Based on agro advisory system, Pande *et al*., (2009) [111] used mobile phone to forecast late blight disease in which actual late blight queries received from farmers were compared and validated with cumulative compo- site rise index taken from existing forecasting models. System based on diagnostic approaches was incorporated with forecasting models.

2.7.4 Physiological strategies

Every crop plant has potential to develop physiological strategies to deal with diseases. These physiological strategies are escape, resistance, tolerance and recovery. The fungus *Phytophthora infestans* attack and affect the crop resulting reduction of the leaf area which directly lower down the photosynthesis process and reduce the crop capacity to produce photosynthetic assimilates require for growth and maintenance of haulm and for tuber bulking. The pathogen directly infected the tuber and reduces the yield & market value of tubers. These infested tubers put for storage in cold storage serve as important source of inoculum. An infected crop also serves as source of inoculum which is really unacceptable in area where potato crop is grown in high proportion. Due to these reasons, two physiological strategies *i.e.* escape and resistance work against late blight disease in potato crop. Disease can be escape by accelerating the early canopy growth without advancing tuber bulking. This may be possible through agronomic practices such as extra nitrogen application (which might delay tuber bulking up to some extent). Advancement in tuber bulking without advancing canopy development can also be one of the escape strategies. This can be achieving by manipulating the physiological age of the seed tubers (Struik and Wiersema, 1999) [142]. Struik, (2010) [143] worked on physiological strategies to cope with disease based on escape and resistance. Escape strategy includes advance or change the entire crop cycle so at the time of pathogen attack, the crop will become mature enough to cope with disease. If potato crop is planted in early October in sub-tropical, it may escape blight attack. The advancing of crop cycle can be done by early planting of crop, planting larger seed tubers *etc* (Struik and Wiersema, 1999) [142]. Accelerate the tuber bulking without advancing it through chemical treatment of foliage may be other escape strategy. Other physiological strategies to cope with late blight disease through resistance include strengthening the race non-specific resistance which results delay in initial infestation and slower development of disease. Race non-specific resistance against late blight is strongly associated with foliage maturity type (Visker *et al*., 2003a, 2003b, 2004, 2005) [158, 157, 159, 156]. The other resistance strategy is influencing the microenvironment around the basal leave which will slow down the development of late blight epidemic and inhibit first infestation. Planting pattern, row to row distance, seed treatment, seed tuber size *etc.* will make such microenvironment which is not conducive to infection by the pathogen.

2.7.5 Biological control

Management of highly destructive disease such as late blight of potato is slightly difficult due to rapid establishment of infection and explosive disease development. So, little information is available regarding biological control as potential alternative against late blight disease. In biological control, living microorganism or abiotic products provide disease protection through production of antibiotics, competition for food and space, induced plant resistance *etc.* Daayf *et al.*, (2003) [37] also studied on biological control of potato late blight by detached leave method, whole planting testing system and *in-vitro*. Shailbala and Pundhir, (2008) [125] observed that *Trichoderma* (formulation) @ 10 g/l and *Pseudomonas* (formulation) @ 10 g/l showed antagonistic behaviour and gave the best results against late blight disease. Various fungi, bacteria and different compost extracts were tested against *Phytophthora infestans* in potato crop (Ghorbani *et al*., 2005; Lamsal *et al.*, 2013) [64].

Kaya *et al*. (2006) [87] evaluated me- tabolites produced by *Xenorhabdus* spp against *P. in- festans*. Bio-agent *Steinernema feltiae* was also studied against late blight both *in vivo* and *in vitro*. Yang *et al.*, (2001) [166] tested metabolites from culture broth of *Xenorhabdus nematophilus* isolated from nematode *Steinernema caropcapsae* for control late blight in potato potted plants and revealed that metabolites @ 25 and 50 mg/l found effective in reducing late blight intensity. Application of *Xenorhabdus* spp. gave most consistent results of biological control against late blight disease (Yang *et al*., 2001) [166].

2.7.5.1 Potential antagonists

Many scientists worked on infection of *Phytophthora infestans* on potato tubers to search for micro-organism as possible antagonists to the test pathogen. Isolates of *Pseudomonas* spp, *Burkholderia* spp., *Streptomyces* spp. and *Trichoderma* spp. were obtained from stems, leaves, tubers and rhizoplane of potato plants. The activity of these micro-organism to A1 and A2 mating type of *P. infestans* were assessed on potato leaves in moist chamber, greenhouse and in field. Reduction in late blight severity occurred with *Burkholderia* spp, *Streptomyces* spp and *Pseudomonas* spp. applied individually or in combination (Lozoya-Saldana *et al*., 2006) [102]. The impacts of potentially effective bio-control agents against late blight would enhance disease management in organic cropping system and its contribution would be of great relevance. A combination of bio-control agents with products such as neem oil could be effective to manage late blight severity and it could be another option to reduce crop losses caused by the pathogen. Among the seven potato phylloplane fungi, only three fungi *viz., Fusarium* spp, *Trichoderma* spp, *Aspergillus* spp showed antagonistic potential against *P. infestans*, causal agent of late blight of potato (Shailbala and Pundhir, 2007) [123].

2.7.5.2 Systemic acquired resistance

Yan *et al.*, (2002) [165] suggest that induced protection elicited by both bacilli and pseudomonad PGPR strains was SA (salicylic acid) independent but ethylene and jasmonic acid depend- ent, whereas systemic acquired resistance elicited by the pathogen and induced local resistance by BABA (β amino butyric acid) were SA-dependent. BABA and phosphoric acid @ 2 g/l involved in systemic acquired resistance reduced late blight significantly and induced expression of defense gene in Kufri Chandramukhi (CPRI, 2014-15) [34].

2.7.5.2.1 Use of endophytic organism

Some endophytic organisms were also tested against late blight of potato. Control of late blight was attempted with arbuscular mycorrhizal fungi (O' herlihy *et al*., 2003) [110]. It was reported that there was reduction of disease progress rate. For potato late blight, this can be an important strategy to reduce crop losses.

2.7.5.2.2 Bio-fungicide

Several commercial formulations of bio-control agents have been tested for efficacy against late blight. Soytong and Ratanacherdchai, (2005) [141] worked on myco-fungicide against late blight of potato and results indicate that *Chaetomium* myco-fungicide could reduce incidence of late blight of potato caused by *Phytophthora infestans* and reduce the population in the soil with significant reduction the potato late blight. Formulation of *T. viride* and *Phytophthora viridicatum* significantly reduced *Phytophthora infestans* sporangial germination and has potential to control potato late blight under control condition (Gupta *et al*., 2004) [69]. Trichotoxin A50 is a brown liquid formulation of natural substances that can induce immunity of plants such as potato, cucumber and tomato to disease by interval spraying at 7-10 days to the plant @ 50 cc/20 lit of water (Suwan *et al*., 2000) [146]. Many reports are available about antibiotic-producing microorganisms tested for bio-control capacity (Behal, 2000) [12]. However, only few antibiotics have been developed as commercial compounds in agriculture. Some of the reasons include their inconsistent efficacy in the field, their instability and the costs related to their production.

2.7.5.2.3 Rhizobacteria

Drenching with plant growth promoting rhizobacteria isolates increased the total weight of tubers per potato plants, in addition to effectively controlling late blight caused by *P. infestans* (Kim and Jeun, 2006) [90]. Beneficial effects reported by plant growth promoting rhizobacteria includes increases in a number of parameters such as germination rate, root, shoot growth, yields etc (Lucy *et al.*, 2004) [103]. *Bacillus pumilus* and *Pseudo- monas fluorescens* induced resistance to *P. infestans* and there was reduction in zoospore formation and germination (Yang *et al.*, 2001) [166]. In *in vitro* and *in vivo* studies, *Pseudomonas*, *Rahnella* and *Serratia* can less- en late blight symptoms by a combination of antibiosis and induced resistance against *Phytophthora infestans* (Daayf *et al.*, 2003) [37]. Therefore, bio-control using plant growth promoting rhizobacteria represents a potentially attractive alternatives disease management approach since they are known to promote growth and reduce disease in crops (Jetiyanon and Kloepperm, 2002) [80].

2.7.5.2.4 Essential oils

Mari *et al.*, (2003) [104] gave the information about the use of natural compounds derived from plants to control late blight in potato crop. The use of biological compounds extracted from plants may be an alternative to conventionally used fungicides to control phyto-pathogenic fungi, due to their being bio-active chemicals such as flavonoids, phenols, tannins, alkaloids, quinons, saponins and sterols (Burt, 2004) [25]. Bio-logically active compounds found in plants appear to be more adaptable, acceptable and safer than synthetic compounds and display a wealthy source of potential pathogens controlling agents (Tripathi *et al.*, 2008) [149]. Amini *et al*., (2012) [5] reported antifungal activity of essential oil obtained from three medicinal plants *i.e. Zataria multiflora*, *Thymus vulgaris* and Thymus *kotschyanus* against phyto-pathogenic fungi. Even Caraway essential oil delayed the onset of late blight for about 10-14 days under field conditions (Hannukkala *et al.*, 2002) [73]. Keskitalo *et al*., (2005) [89] worked and reported that caraway oil delay the onset of disease for 14 days. The control activity of this oil is based on prevention of late blight sporangia production and growth at low oil concentration. Essential oils are oily liquids obtained from plants through fermentation, enfleurage, extraction and steam distillation (Burt, 2004) [25]. Essential oils have two prominent features *i.e.* low toxicity for people and environment due to their natural properties and low risk for resistance development by pathogenic microorganisms (Dafererra *et al*., 2000) [39].

2.7.5.2.5 Plant extracts

Plant extracts are obtained by filtration, distillation and evaporation (Wang *et al.*, 2004) [162]. The work on plant extracts with anti-oomycetes activity has been increased over the years and efficacy of plant extracts against pathogen has also been demonstrated. Several preliminary *in vitro* studies has been conducted in China and India (Cao *et al*., 2003; Deepa *et al*., 2004) [26, 41]. Six extracts from plant material (*Galla chinensis*, *Potentilla erecta*, *Rheum rhabarbarum*, *Salviae officinalis*, *Sophora flavescens*, and *Terminalia chebula*) were tested for controlling effects against the infection of *Phytophthora infestans* on detached potato leaves, seedlings and tuber slices. On detached leaves, *G. chinensis* was the best. On seedlings, *R. rhabarbarum* showed the best inhibiting effect (Shutong Wang *et al.*, 2007) [133]. Wang *et al.* (2004) [162] reported that *Inula viscosa* reduced 90% late blight severity in potato plants. Extracts of *Terminalia chebula* and *Galla chinensis* were also found effective to control late blight of potato and 30% and 10% inhibition of disease were noticed respectively (Cao *et al.*, 2004) [25]. One of the most effective treatments was extract of garlic cloves which at 1 or 2 percent completely inhibit the zoospore formation and colony growth of pathogen the statement supported the references (Cao and Van Bruggen, 2001;Halama and Haluwin, 2004) [27, 71]. Ahn *et al.*, (2005) [3] reported that methanolic extract of galls (gall caused by an aphid, *Schlechtendalia chinensis* in nutgall sumac tree) reduced approximately 90% late blight severity. Extract derived from *Pseudarthria viscida*, *Cassia tora* and *Catalpa ovata* have also inhibited growth of *Phytophthora infestans* under laboratory condition (Kim *et al.*, 2004; Cho *et al.*, 2006) [91, 28].

2.7.5.2.6 Other products

Scheuerell and Mahaffee (2002) [118] reported that combination of water based extract fermented tea and plant compost (known as compost tea) as foliar spray in potato not only improve soil fertility but also control pathogen and pests. This compost tea may be considered as one of the best option to control of late blight disease of potato (Rashidul Islam *et al*., 2013;Al-Dahmani *et al*., 2005 ; Scheuerell and Mahaffee, 2006) [116, 4, 119].

2.7.6 HPR

Due to rapid development of new strains of *Phytophthora infestans*, host plant resistance appears eco-friendly and economic feasible approach for late blight management. Shailbala and Pundhir, 2008; Njualem *et al*., 2001) [125, 109] also reported variation in resistance against late blight among potato cultivars. Resistant potato cultivars could easily destroyed by newer strains of pathogen since single gene control the resistance. Potato cultivars with high level of resistance can be helpful and allow growing even in cool season without use of fungicides. Durable or polygenic or field resistance is generally controlled by several minor genes which give slow blighting effect. Fry, (1977) [60] reported that potato cultivars with durable or polygenic resistance showed significantly less values of area under disease progress curve and low infection rates as compared to susceptible cultivars. Many released and improved resistant potato cultivars lost their resistance against disease but was able to tolerate the disease and gave satisfactorily yield (GLIB and CIP, 2004a; Jones, 1998; ATTRA, 2004) [66, 29, 83, 11]. Shtienberg *et al*., (1994) [132] also reported that compatible races of pathogen *Phytophthora infestans* fastly broken down race specific oligogenic resistance (CIP, 1989; FAO, 2008;Popokova, 1972) [29, 48, 114]. Shtienberg *et al*., (1994) [132] concluded that use of resistant cultivars can be one component to be use in late blight management for tropical condition. Initially resistance gene was identified in *Solanum demissum* which provided base to transfer resistance gene from it and to develop resistant cultivar *i.e.* Kufri jyoti (having R gene 3.4.7) for commercial cultivation in 1968. Low inoculum load and shorter late blight congenial period was important factor behind popularity of this cultivar in several part of country till date. Shekhawat, (2000) [129] reported that *Solanum tuberosum* subsp *andigena* have also been exploited for develop- ment of resistant cultivar. late blight resistant cultivars have capacity to delay the disease onset and further disease development so fewer fungicidal sprays on these resistant cultivars can effectively manage the disease supported the references (Agrios, 2005;Binyam *et al*., 2014; Kirk *et al*., 2001;Song *et al*., 2003) [2, 18, 92, 140].

2.7.7 Bio-technological methods

Potato is considered as poor man food and late blight as catastrophic disease. Late blight free potato will have direct impact on people food security and income in developing countries. Worldwide use efficiencies of land, water, nutrients and energy can greatly improve by achieving disease free potato tubers but practically it is not possible. To get disease free potato tubers, bio-technological approach against late blight can be the best option. The knowledge on molecular biology and genetics of interaction between plant and oomycetes mainly focused on discovery of many resistance genes, numerous effector proteins and analysis of their mode of action which provide important information required for development of durable resistance (Haverkort *et al*., 2009) [74]. A novel approach is mainly based on cisgenic modification which depends on marker free gene pyramiding with their spatial and temporal deployment. This cisgenic modification approach with potato's own gene is societally acceptable and also results in simplification in the legislation on the use of cisgenic modification approach (Haverkort *et al*., 2009) [74]. So, DuRPh (Durable Resistance against *Phytophthora infestans*) programme were made which focus on durable resistance in potato crop. In DuRPh programme, cloning, transformation and selection of desired resistance gene ids important part of process to develop late blight resistance. The main aim of this programme is to develop cisgenic potato variety with durable resistance feature against late blight disease. Some important features of DuRPh programme includes Genetic modification: This includes detection, isolation, cloning and transformation of gene from wild species into existing varieties through *Agrobacterium tumefaciens*, a bacterial vector. The plantlets regenerated from callus are screened to assess for resistance. Important point is that they should have the same phenotype as the wild variety into which resistance genes introduced Cisgenic approach: In this approach, natural resistance genes from plant itself or from crossable species are used and the choice of cisgenic was mainly based on availability of resistance gene in potato crop. Jochemsen, (2008) [81] reported that this approach was ethically more acceptable to the public. Through gene pyramiding, several resistance genes are inserted to reduce the rapid break down. In this programme, no markers are used so variety obtained will be maker free. PCR techniques are used to assure that resistance gene is present in genotype show resistant against all known pathotypes of *Phytophthora infestans*. In different varieties at different sites at different times, various combinations of stacked genes are de-ployed resulting spatial and temporal seperated de-ployment of resistance gene. The start and end product during this programme is potato varieties which consist of potato genes only. In this programme, no new varieties developed and only point is that in old variety resistance gene of wild potato species were incorporated. The exploitation of the R genes which is not to be homologous to previously discovered ones, is possible by protecting the intellectual property and making them available (not exclusively) to private potato breeding companies.

2.7.8 Compost

The decomposition of organic wastes leads to the formation of the most used soil amendment, the compost. Balanced use of fertilizers increases soil fertility without environmental degradation in a sustainable way (Shrestha *et al*., 2020) [131].

3. Conclusion

Late blight of potato is the most dreaded disease and will continue to remains as the pathogen is evolving at a fast rate and adapting to new environments and hosts. Due to highly variable nature of late blight pathogen, preventing the establishment of infection is perhaps the most interesting strategy for management of late blight. Detaining pathogen development after infection is difficult. So application of control measures can reduce the survival period as well as the effectiveness of the source of initial inoculums which prevent sporangia germination (germ tube formation) and/or zoospore germination. Late blight forecasting models will help the growers in managing this serious disease. Farmers should contact their local extension office regarding disease forecasting and accordingly they can apply the preventive control measures. Use of resistant varieties along with physiological strategies for disease management can be the best option. Cultural practices for disease management always consider the first line of defense while biological control can become an integral part of management programme aimed at controlling late blight. Biotechnological approaches can help in development of durable resistance varieties. So management strategies include disease forecasting system, host plant resistance, physiological strategies, cultural control, biological control and biotechnological approach, as already discussed certainly can become an integral part in management programme aimed at controlling late blight in both conventional and organic cropping system of potato. So, alternative non-fungicidal eco-friendly control measure against late blight should be implemented under a holistic approach. As more and more information is being generated, there is a need to develop an appropriate disease management strategy based on farmer friendly information technology.

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