Necessities and Strategies of Plant Biosecurity in the context of Plant Disease

Shinee De, Ayan Pramanik, Debargha Patra, Poulomi Gangopadhyay, Birendranath Panja

Plant biosecurity employs a strategic socio-economic approach aiming the protection of natural and managed plant systems from alien as well as emerging indigenous pests and pathogens by the regulation of both intentional and unintentional introductions. Phytopathogens pose a substantial threat to the plant ecosystems by compromising their productivity, sustainability and biodiversity. Unwanted invasion of the phytopathogens has accelerated mostly with the exponential growth of international trade of 'plants for planting', as an externality cost of globalization. Several new records on deliberate introduction of pests and diseases have put forth the newest fear - 'Agroterrorism'. In the rising background of potential biothreats, plant biosecurity system is the need of the era, demanding the perfect amalgamation of knowledge and efficient risk analysis tools like early detection, accurate diagnosis and rapid response, to minimise the subsequent impact. In this context, idea of the 'Biosecurity continuum' stands inevitable, stating the need of strategies starting from the offshore or pre-border zone, border zone upto the post-border area. Advances in the knowledge and research in plant pathology, are crucial for formulating these strategies. Fundamentals of biosecurity strategies lies in risk analysis, risk assessment and rapid response. Various diagnostic tools of phytopathology, like molecular methodologies, imaging technologies, specialized biosensors etc facilitate accurate, on-site diagnosis of disease. Whereas, need-based enforcement of legislations such as, issuing import permits, phytosanitary certificates, post entry quarantine, inspection at point of entry etc. can be upgraded by incorporation of the knowledge on the nature of potential phytopathogens, their host range etc.

Keywords: *Plant biosecurity, Phytopathogens, Diagnostic tools, Phytosanitary legislation*

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Introduction

The term "biosecurity" originates from Greek words "bios" (life) and Latin word "securitas (protection) meaning protection or safety or freedom of living organisms (plants, animals and humans) from biological threats posed by the intentional and unintentional introduction of pathogens, pests, invasive species, the introduction and release of genetically modified organisms (GMOs) and their products. Eventually, plant biosecurity refers to the set of policies, regulation, measures and action taken with objectives to prevent the entry, spread and establishment of emerging and endemic harmful pests, pathogens (fungi, bacteria, viruses, nematodes) and invasive species, from alien and emerging indigenous sources, that threaten the productivity and biodiversity of crops, forest, natural ecosystems, safeguard the trade, food security and farmers' livelihood and diminish reliance on chemical control method. The prevention, surveillance and early detection, rapid response and containment, management and control for management of invasive alien pests (weeds, insects and pathogens) by federal, state and local government, industries and other stakeholders, are the vital component of plant bio-security. Understanding the need for biosecurity of natural or crop plants from the plant disease primarily brings the plant pathogens like fungi, bacteria, virus, viroids, protozoa, phytoplasma, spiro plasma etc. into the scenario. These pathogens pose a substantial threat to the plant ecosystems by compromising their productivity, sustainability and biodiversity. Broadly, the plant biosecurity can be categorized as a subset of crop protection, concerned with restricting the unwanted invasions or the spread of pathogens. Crop protection measures play one of the most pivotal roles in ensuring global food security, but developing effective disease management strategies often takes time.

Why plant biosecurity from plant disease

In the modern era, globalization has erased barriers to the movement of plants, their parts, and products across states, countries, and continents. This has facilitated the introduction and spread of numerous alien, emerging, and endemic plant diseases, enhancing risks associated with global trade and travel. Introduced pathogens may reach epidemic proportions, cause catastrophic yield and quality losses, threaten food and nutritional security, create economic instability among small and marginal farmers, and increase reliance on excessive pesticide application, endangering human health, environmental sustainability, and non-target beneficial organisms. They may disrupt ecological balance by displacing indigenous flora, cause long-term environmental degradation, and affect safe trade and market access. Climate change can further alter pathogen population dynamics, enabling the evolution of new races, biotypes, and strains, increasing virulence, dissemination, host jumping, and disease emergence. Examples include *Phytophthora infestans* shifting from potato to tomato, *Fusarium oxysporum* f. sp. *cubense* TR4 infecting a wider banana range, *Magnaporthe oryzae* expanding from rice to wheat, barley, and grasses, *Ralstonia solanacearum* attacking banana, groundnut, jute, ginger, and ornamentals, *Xylella fastidiosa* moving from grapevine to olive, citrus, almond, coffee, and ornamentals, *Colletotrichum gloeosporioides* forming a species complex infecting mango, papaya, citrus, apple, chilli, and ornamentals, and *Puccinia graminis* (Ug99) expanding to multiple cereals (Lahali et al., 2024). Host range expansion is linked to mutation, recombination, horizontal gene transfer, resistant variety selection pressure, climate change, and global movement of planting material.

Historic epidemic events illustrate the impact of invasive pathogens: the Irish famine (1845–46) due to potato late blight (*P. infestans*), Bengal famine (1942–43) due to rice brown spot (*Bipolaris oryzae*), coffee rust in Ceylon (1869), grapevine downy mildew in France, Southern corn leaf blight in the USA (1970) caused by *Bipolaris maydis* race T highlighting dangers of monoculture, and global outbreaks of kiwifruit bacterial canker (*Pseudomonas syringae* pv. *actinidiae*). Pathogen introduction may occur through carrier host plants, insect vectors, birds, natural air or water currents, and sometimes inert materials like gunny bags and polythene packaging. Global trade in exotic ornamental plants further increases invasion events; in the UK, exotic plants number ~73,000 species while native flora includes only 1,500 species (Perrings et al., 2005). Repeated introductions and propagation have enabled naturalization of non-native flora. *Phytophthora ramorum*, causing Sudden Oak Death, spread widely through ornamental plant trade. The continued rise of new disease records 617 new distribution records of 283 plant pathogens identified in 2021 (Ristaino et al., 2021) highlights the seriousness of this pathway.

Germplasm exchange for crop improvement also demands strict biosecurity. A decade-long survey in India (1975–2015) on imported oilseed and vegetable brassica germplasm from 23 countries revealed persistent presence of *Alternaria brassicicola* (65.5%) and *Xanthomonas campestris* pv. *campestris* (17.8%), along with 16 other pathogens, with most interceptions from the USA (26.3%) and Canada (24.0%) (Akhtar et al., 2017). Alongside exotic pathogens, indigenous pathogens are also emerging rapidly, possibly due to competition with exotic organisms, climate change, and widespread use of hybrids. New host ranges of begomo viruses in India (Sharma et al., 2018) and increasing severity of diseases once considered minor foliar blight of wheat, sheath blight in maize and paddy, bract mosaic of banana, necrosis of sunflower and groundnut illustrate this resurgence (Khetrapal et al., 2007).

Deliberate introduction of plant pathogens has created the modern threat of agroterrorism. Diseases associated with agroterrorism concerns include wheat stem rust (*Puccinia graminis tritici*–Ug99), rice blast (*P. oryzae*), late blight (*P. infestans*), Panama wilt TR4, soybean rust (*Phakopsora pachyrhizi*), maize leaf blight (*B. maydis*), maize lethal necrosis (Maize chlorotic mottle virus), citrus canker (*Xanthomonas axonopodis* pv. *citri*), coffee rust (*Hemileia vastatrix*), cassava mosaic virus, and bacterial wilt (*Ralstonia solanacearum*). The unexpected outbreak of a new recombinant cotton leaf curl virus strain in Northwest India (2015), distinct from CLCuMuV and CLCuKoV-Bu, suggested possible malicious introduction (Datta et al., 2020). In June 2025, the arrest of a Chinese researcher smuggling the cereal-destroying fungus *Fusarium graminearum* into the USA raised further fears of agroterrorism (The Hindu, 4 June 2025). Against this rising background of biological invasions, a strong plant biosecurity system with early detection, accurate diagnosis, and rapid response has become essential.

Table 1. List of the Organisms that are potential threat to India in Bio security

Disease / Pathogen	**Type**	**Primary Host Crops**	**Why it is a threat if introduced to India**
Wheat Blast (*Magnaporthe oryzae* pathotype Triticum)	Fungus	Wheat	Causes sudden spike disease; severe yield losses; spreads rapidly under humid conditions.
Wheat Stem Rust Ug99 (*Puccinia graminis* f. sp. *tritic*i)	Fungus	Wheat	Highly virulent strain; can overcome many wheat resistance genes; threatens national wheat production.
Ralstonia solanacearum Race 3 Biovar 2	Bacterium	Potato, tomato	Causes brown rot; survives in cool climates; difficult to eradicate once established.
Citrus Black Spot (*Phyllosticta citricarpa*)	Fungus	Citrus fruits	Causes fruit spots and premature drop; affects export quality severely.

Citrus Canker exotic strains (*Xanthomonas citri* variants)	Bacterium	Citrus	More aggressive variants could devastate orchards and spread via wind-driven rain.
Soybean Rust aggressive exotic strains (*Phakopsora pachyrhizi*)	Fungus	Soybean	Can destroy leaves rapidly; reduces yield drastically; spreads via wind.
Potato Wart (*Synchytrium endobioticum*)	Fungus	Potato	Quarantine pathogen; causes severe deformities; persists in soil for decades.
Potato Cyst Nematode exotic pathotypes (*Globodera rostochiensis*, *G. pallida*)	Nematode	Potato	Causes major yield loss; spreads through soil and planting material; difficult to contain.
Fire Blight (*Erwinia amylovora*)	Bacterium	Apple, pear	Highly destructive in temperate zones; can kill entire trees; major orchard threat.
Banana Blood Disease (Blood Disease Bacterium – *Ralstonia* sp.)	Bacterium	Banana	Extremely destructive in Southeast Asia; could threaten India's large banana industry.
Pierce's Disease (*Xylella fastidiosa*)	Bacterium	Grapes, citrus, olive	Causes vine decline; has devastated vineyards abroad; spreads via insect vectors.
Sudden Oak Death (*Phytophthora ramorum*)	Oomycete	Oaks, ornamentals	Kills trees rapidly; threatens forests and nursery industries.
Karnal Bunt exotic aggressive strains (*Tilletia indica* variants)	Fungus	Wheat	More aggressive strains could impact export markets and yield.

Strategies of plant biosecurity from plant disease: Biosecurity continuum

Plant biosecurity approach aims to seek a holistic combination of strategies which primarily would resist the introduction, spread and establishment of invasive alien species at a nation or region's borders. But it is nearly impossible to implement separate biosecurity strategies for each invasive species due to their diversified risks, unpredictable magnitude of impacts, rapid spread and limited resources for timely effective response. Hulmes et al. (2013) visualized the concept of a common framework, namely the 'biosecurity continuum', rather than prioritising any particular sector (Figure 1). This continuum idealizes biosecurity operations staring from the offshore or pre-border zone, border zone up to post-border area. Pre- and post- border operations are mostly accomplished by the trade arrangements of the National Plant Protection Organisations (NPPOs). Pre-border operations focus on international and domestic collaboration for risk assessment and information sharing. Border operations involve import regulations and export certification, while post-border efforts emphasize on vigilance and preparedness for unexpected biosecurity threats.

A detailed understanding of the plant biosecurity continuum leads to the basis of all the operations carried out in different phases, *viz*. risk analysis, risk assessment and rapid response. All three key activities are strengthened on the pillar of a few methodologies. Considering the plant disease point of view for the prevention of introduction, establishment and spread of the phytopathogens, methodologies involved are pre-border, border, post border biosecurity, early detection and diagnosis, surveillance, emergency response systems, use of resistant varieties, farm level biosecurity, awareness and training, international cooperation and research and preparedness and enforcement of legislation which are considered as most crucial.

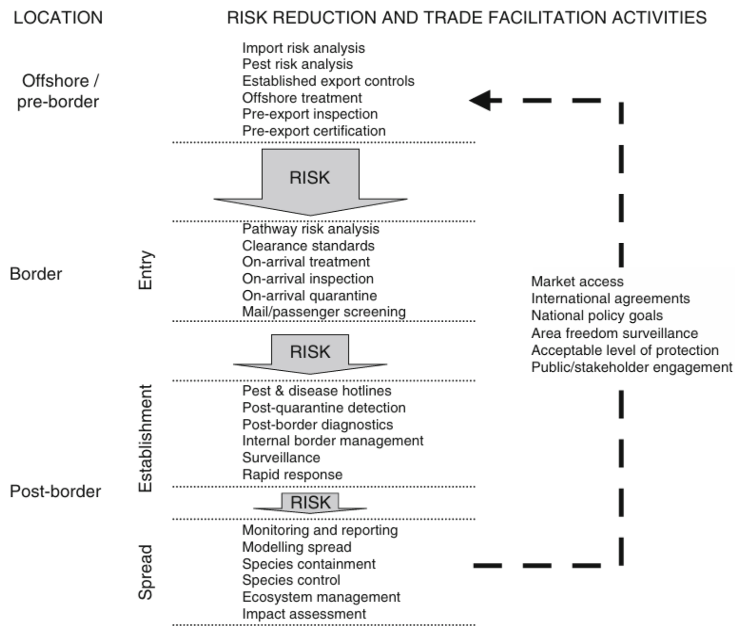

Figure 1. Framework of plant biosecurity continuum summarized by Hulmes et al., 2013

1. Pre-border biosecurity from plant diseases

It is the first line of defense aiming to stop pathogens before entry into a country. Pest Risk Analysis (PRA) or Import Risk Analysis (IRA) is done through pest identification (present in exporting country, absent or limited in importing country, potentially harmful), evaluation of probability of entry (survival during transport, trade volume, life/disease cycle, pathways like seeds, fruits, wood, soil), establishment (climate suitability, reproductive ability), spread (wind, insect, human transport) and economic impact (yield loss, protection cost, environment loss, livelihood, export restriction). Based on this, decisions are taken on import permission or need of phytosanitary measures (import permit, phytosanitary certificate, fumigation, heat treatment, pest free area, post entry quarantine, prohibition). PRA must be completed before allowing plant imports. Regulations may include prohibited species, restricted commodities, approved exporting countries and import permits. Importing country may demand phytosanitary certification ensuring disease-free material. Pre-export inspection of nurseries, fields, packing houses and pre-shipment treatments (fungicides, hot water, fumigants, seed disinfection, tissue culture sanitation) are required. Offshore surveillance helps update risk lists. Accredited production certificates confirm disease-free production sites and certified nurseries.

2. Border biosecurity from plant diseases

It includes measures at seaports, airports and land frontiers to detect, intercept and contain plant materials to prevent pathogen entry. Quarantine inspection of seeds, planting material, fruits, vegetables, wood products and soil-contaminated goods is done. Verification of phytosanitary certificate, import permit, treatment certificate and origin is essential. Sampling and laboratory testing detect fungi, bacteria, viruses and nematodes. Minor contamination is treated with fumigation, chemicals, hot water and seed treatment. Mail and passenger screening (declaration, X-ray, sniffing dogs, manual inspection, confiscation, disposal) stops illegal or risky plant materials. Consignments may be detained for incomplete documents, symptoms or pending tests. If quarantine disease is detected, shipment is rejected, re-exported or destroyed; some materials are allowed under post entry quarantine.

3. Post border security from plant diseases: It includes all actions taken inside a country after the plants or their products have entered with the objective of early detection, rapid containment, prevent establishment and spread and protect crops, forest and ecosystems.

a) Prevent establishment of pathogens: The activities needed to done here are:

- **Establishment of disease hotlines:** A dedicated phone/toll free number, mobile app, WhatsApp, SMS, online reporting system like email, website are needed where farmers, nursery and seed traders, extension workers or border staff or the general public can report early about the unknown symptoms/diseases, suspect unknown pathogens entry, sudden outbreak and spread and strengthen the surveillance network. Observation of disease symptoms, reporting to the stakeholders, expert review and decision about the symptoms and urgency, field investigation, action are also desirable.

- **Enforcement of post entry quarantine diagnosis and detection**: It is the testing and identification of pathogen in plants kept under post quarantine facility. The main purpose of this step is to detect the latent infection, identify seed-borne, systemic or slow developing pathogens and support in taking decision on final release or destroy pathogens. Here the imported plants/ planting materials are grown under controlled conditions after entry and before the plants are finally released for cultivation to check the latent/ hidden infection caused by slow developing pathogens like viruses and systemic fungal and bacterial pathogens. Some pathogens (viruses, phytoplasma, vascular wilt, systemic fungi) do not show symptoms immediately, have long incubation period and are internally seed / plant borne. Plant materials are kept in government quarantine station, approved research institutes, accredited greenhouses and screenhouses with insect proof nets. Imported plant materials are provisionally released from the point of entry and are send to PEQ (post entry quarantine) facility where plants are grown under controlled condition in isolated greenhouse, no contact with local crops and insect proof environment. Regular checking for the appearance of diseases is done. Laboratory testing if required is also done. Plants are kept for a few weeks for annual crops and several months for perennial crops.

- **Execution of internal border management**: It means controlling movement of plants, plant product, soil and related material within a country to prevent the spread of the disease from one region to other, contain the disease within the affected area, protect the pest free areas and support eradication programme. It deals with the containment of diseases within the affected zones, protect pest free areas, stop the spread of invasive pathogens and support the eradication programme. The main ladder-steps in this action are to define quarantine zone, restrict movement of plant material, check the post, courier and inspection points, permit the plant movement having phytosanitary, treatment and origin declaration certificates, treat the plants before movement, trace the consignment after transport and finally aware the public

- **Strengthening plant disease surveillance system:** Surveillance is the systemic collection, analysis and interpretation of data on plant disease to detect new incursion of disease, changes in disease distribution, prove pest free status for trade and outbreak at early stage. It may be general/ passive surveillance (report from farmers, extension workers, researchers and public), targeted/ active surveillance (organized survey by authorities by targeting high disease risk areas and specific crops), sentinel plot (monitoring on farms, nurseries and research plots), pathway surveillance (ports, frontiers, markets, nurseries, borders). Field inspection, spore trapping, remote sensing, GPS/GIS and molecular tools are the tools used in surveillance. Surveillance process involved planning of survey, field observation, sample collection, laboratory diagnosis, data analysis, reporting and action.

- **Enaction of rapid response:** It refers to the immediate organized action taken after detection of a new or exotic disease/ pathogen to stop it from establishing and spreading, contain the outbreak quickly, protect the pest free zones, eradicate if possible and minimize economic and environmental damage. The key steps in this action are early detection and alert, confirmatory diagnosis by morpho-molecular means, formation and execution of quick response team, survey immediate for delimiting the extend of disease progress and determine infested vs disease free zones, restriction of movement through quarantine, adoption of eradication or control measures, decontamination, public communication and monitoring after action

b) Prevention of the spread of pathogens: The activities done here are:

- **Post border monitoring and reporting:** It denoted to the continuous observation and documentation of plant health inside a country after entry of plants or detection of new pathogen/disease to track the disease presence and spread, evaluate the success of control/ eradication, detect re-occurrence, provide data for decision making and maintain pest free status of trade. It involves follow up survey (field inspection, trap monitoring, symptom check), diagnostic confirmation (Microscopy, culture, ELISA/PCR), data recording systems (disease database, GIS map and surveillance log), disease status determination (absent, present but controlled, eradicated, widely distributed),reporting channel (National level - NPPO, State Agriculture Department, research institute, International level – IPPC) and evaluation of control measures (quarantine zone working, treatment effective, further action needed)

- **Modelling spread:** Modelling pathogen spread is the use of mathematical, statistical, and spatial tools to simulate how a plant pathogen may enter, establish, and spread in a new area and helps to predict where, how fast, and how severe an outbreak can become. It predicts area at risk, estimate speed of spread, identify entry pathways, support quarantine and containment, guide surveillance placement and plan eradication strategies. Pathogen (reproduction rate, survival ability, latent period, host range etc), host (distribution of crops, susceptibility level, cropping pattern), environment (temperature, rainfall, humidity, wind direction/speed) and human (trade of plants/seed, transport routes, farm tools & machinery, passenger movement) factors are the key components of spread of pathogens.

  Types of spread models are 1. Spatial models (GIS-based) - Used to map disease risk geographically using GIS tools, remote sensing GPS data and to identify hotspot and predict spread corridor. 2. Epidemiological models - SIR (Susceptible infected removed model) model for fungal disease spread while SEIR (susceptible exposed infectious removed) model includes latent period, viral diseases, logistic growth, population expansion and soil borne pathogens. 3. Climate-driven models – predict diseases based on weather suitability. 4. Dispersal models - spread mode - Airborne spores, wind trajectory modelling, soil borne disease, local diffusion, insect-vectored, vector population dynamics, human-assisted trade network modelling. 5. Stochastic models - include randomness, rare introduction and early invasion. The data sources used for the purpose are obtained from field surveillance, weather station, satellite data, trade record, transport network map, historical output data. It plays an important role in assessment of import risk identification in high-risk entry points, predict establishment zones, emergency response, delimiting surveys, containment, define buffer zones, eradication, target high risk foci.

- **Species containment:** It means restricting pathogen to a limited area to prevent its spread to new regions where it could cause economic or ecological damage. It is done to prevent spread beyond the infested area, protects pest-free zones, reduces economic losses, buys time for research and management and supports long-term suppression. It is executed when pathogen is already established; eradication is too costly or impractical, spreading rate is still manageable and clear geographic boundary exists. The strategies followed in this regard are 1. Quarantine zoning like infected zone, buffer zone and pest free zone 2. Movement control by banning plant and soil movement, certifying planting material, clearing vehicles and machinery and exercising checkpoints and inspections. 3. Physical barriers by establishing net houses, windbreaks, drainage barriers (soil pathogens) and insect-proof screens (for vector borne diseases). 4. Host management by removing infected plants, rotating crops, growing resistant varieties and destroying volunteer hosts. 5. Vector control - it is critical for virus and bacterial diseases management. It includes insecticide application, use of sticky traps, bio-control agents and removal of weeds. 6 Surveillance and monitoring by paying regular field surveys, trapping programmes, remote sensing, diagnostic testing and early detection prevents escape. 7. Public awareness and compliance through farmer education, reporting hotlines, legal enforcement. Illegal movement, latent infections, asymptomatic carriers, insect vectors crossing boundaries, farmer non-compliance are some of the challenges in species containment.

- **Species control:** It refers to the measures taken to reduce the population, impact, or damage caused by an invasive pathogen to an acceptable level. It is practiced to lower pathogen population, reduce crop loss, protect environment, prevent further spread and maintain production stability. Major control approaches followed here are 1. Cultural control like crop rotation, deep ploughing, field sanitation, removal of infected plants, adjust planting time, proper spacing etc are followed for modifying the farming practices to make the conditions unfavorable for the diseases/pathogens, 2. Physical control trailed by soil solarization, hot water seed treatment and burning infected debris. 3. Biological control includes use fungal biological agents like *Trichoderma, Bacillus subtilis, Pseudomonas fluorescence*. 4.Chemical control utilizes, fungicides, bactericides, nematicides and insecticides (vector control). 5.Host resistance employed resistant varieties, tolerant cultivars, GM resistance (where approved) 6. Integrated disease management (IDM). 7. Regulatory control exploit movement restrictions, certification of planting material, seed health testing and quarantine measures. Resistance development, cost of repeated treatments, environmental impact and climate influence on control success are some of the challenges under the species control.

- **Ecosystem management:** It means maintaining healthy, balanced agro- and natural ecosystems to reduce the risk of pathogen introduction, establishment and spread. It focuses on increase ecosystem resilience, reduction of pathogen buildup, promotion of natural enemies, maintenance of biodiversity and lower dependency on chemicals. It is based on key principles like increase diversity promotes soil and plant health, balances ecosystem and encourage population of bioagents and reduces plant diseases. Major components of ecosystem managements are 1. Biodiversity conservation highlights mixed cropping, crop diversification, agroforestry and maintaining wild plant diversity and reduces monoculture vulnerability. 2. Soil health management endorses the application of organic manure and biofertilizers, enhances microbial population and promotes disease suppression, reduces tillage, preserves soil life, healthy soil microbe and competes with pathogens. 3. Water and microclimate management approve proper drainage, avoid waterlogging, advocate controlled irrigation, windbreaks, Reduces favourable conditions for fungal pathogens. 4. Landscape-level planning – creates buffer vegetation zones, avoids clustering of same crop and manages corridors that aid pathogen/ disease movement. 5. Use of native and resistant species may help native species adapted to local pathogens and resistant cultivars reduce the disease load. 6. Reduced chemical disturbance arising out of overuse of pesticides, protect beneficial organisms, minimize resistance development, uninterrupted ecosystem balance.

- **Impact assessment**: It is the evaluation of the potential economic, environmental, and social consequences of introducing or spreading a plant pathogen. It is done to estimate possible damage, support quarantine decisions, prioritize high-risk pests, guide management strategies and justify regulatory actions. The types of impact assessed are 1. Economic Impact -Yield loss, quality reduction, increased production cost, market loss (export bans) and cost of control measures. 2. Environmental Impact - Loss of biodiversity, damage to native plants, ecosystem imbalance and pesticide overuse effects. 3. Social impact - Farmer income loss, rural unemployment, food security risks and impact on livelihoods 4. Trade impact - Import/export restrictions, loss of international market access, certification requirements. Impact assessment has steps like identify the pathogen, determine host range, assess establishment potential, estimate spread ability, evaluate economic and environmental losses, assess control feasibility and overall risk rating. Uncertain future climate, limited data on new pests and hard to quantify ecological damage are some of the limitations.

Diagnosis, detection and surveillance of phytopathogens

Diagnosis is the process of identifying a disease and its associated pathogen whereas diagnostics describe the tools and tests used for this. The direct diagnosis involves easy, less time-consuming, common techniques and sophisticated technologies are included under indirect diagnosis.

1. Direct diagnosis

- **Diagnosis based on disease symptom and culturing and identification of the pathogen**

A large number of plant diseases can be identified through visual examination of symptoms, while hand lenses and binocular microscopes help observe fungal asexual structures (acervuli, pycnidia, sporodochia, synnema) and sexual fruiting bodies (cleistothecia, perithecia, apothecia, pseudothecia). Compound microscopes detect fungal mycelia, spores, and bacteria, whereas scanning and transmission electron microscopes reveal virus particles. Automated leaf disease diagnosis systems using pattern analysis, AI, and IoT sensors now enable rapid field-based detection (Jafar et al., 2024). Standard identification still involves isolating the pathogen in pure culture, inoculating healthy plants, observing symptom development, re-isolating the organism, and comparing it with the original isolate to fulfil Koch’s Postulates. Several selective media and incubation conditions support accurate isolation, including Malachite Green Agar (for *Fusarium*), Ko and Hora medium (for *Rhizoctonia*), and modified PDA or potato dextrose agar (for *Sclerotium rolfsii*). Susceptible plant materials are also used as bait to attract pathogens: cucumber and lupin seeds (for *Pythium* and *Phytophthora*), sesame seed (for *Pythium*), apple and pear fruits (for *Phytophthora*), cucumber slices (for Oomycetes), green pepper fruits (for *Phytophthora capsici*), oak and azalea leaves (for *Phytophthora ramorum*), carnation petals (for *Fusarium*), and grass leaves (for *Pythium* and *Rhizoctonia*), including to encourage distinctive spore formation of *F. proliferatum* from infected onion bulbs.

- **Molecular diagnostic and detection techniques**

Traditional diagnostic techniques are often time-consuming, and obligate plant pathogens (downy mildew, powdery mildew, rust, etc.) are non-culturable. Virus symptoms vary with cultivars, and threats may arise from particular subspecies, races, or variants that cannot be distinguished visually. These difficulties necessitate accurate, specific, and sensitive diagnostic tools that identify pathogens at the molecular level. Molecular diagnostics such as basic PCR, qPCR, RT-PCR, and multiplex PCR are widely used for phytopathogen detection. Significant advances include qPCR for detecting *Sclerotium cepivorum* sclerotia from soil, identification of *Rhizoctonia solani* anastomosis groups, quantification of *Plasmodiophora brassicae* (club-root) from soil, IRAP-PCR differentiating *F. oxysporum* f. sp. *lactucae* race 1, and sensitive RT-qPCR detection of *Phytophthora ramorum* compared to selective medium isolation. Despite high sensitivity, PCR may require large target tissue or multiple assays. Isothermal amplification technologies like LAMP, RCA, and RPA overcome these issues by amplifying DNA/RNA at constant temperature without a thermocycler, with lower detection limits and ability to differentiate related species or non-target strains. These methods are used for field diagnosis of fire blight, club root from soil and seed samples, leaf blotch fungi of wheat, and race-specific detection of *F. oxysporum* f. sp. *vasinfectum* race 4. RPA has shown promise for field detection of plant viruses with DNA genomes (Banana bunchy top virus, Tomato yellow leaf curl virus, Bean golden mosaic virus) and RNA genomes (Rose rosette virus). Immunological techniques like FISH and ELISA are also widely used; ELISA is common for viruses, though less effective for bacteria. DBT, Govt. of India, promotes ELISA kits and DNA-Chips for virus detection in high-value crops. 'Pocket Diagnostic' lateral flow devices (LFDs) provide on-site detection within 10 minutes, even from woody tissue, though with lower accuracy. LFDs exist for *Rhizoctonia solani* in soil and *Peronospora destructor* sporangia using monoclonal antibodies and have been in use since the 1990s. RPA-LFD combinations have enabled on-spot detection of *Fusarium oxysporum* in field and greenhouse conditions (Hu et al., 2024). Challenges include high cost, false positives, and short shelf life of enzymes and primers, which can hinder molecular diagnostics.

2. Indirect diagnosis or surveillance of disease

Prevention of the spread of an invasive pathogen or halting of the epidemic at very early stage are quite essential. The vast areas of cultivated plants in vulnerable areas must needed to be monitored regularly. In such cases, pre-symptomatic detection techniques, aerial monitoring for locating any infection foci are found to be superior to mere crop walking or visual inspection or the identification of pathogens.

- **Surveillance using imaging or optics technologies**

Imaging technologies capture visual, spectral, or thermal information from plants to detect infection, stress, and physiological changes, and although less specific than molecular tools, they are valuable for large-scale monitoring. RGB imaging detects visible symptoms such as leaf spots, blight, rust pustules, wilting, chlorosis, and necrosis and is widely used in field scouting, smartphone-based diagnosis, and AI apps. Multispectral imaging measures reflectance in red, green, blue, and NIR bands using indices like NDVI for plant health, NDWI for water stress, and GNDVI for nitrogen content, enabling early detection of fungal, bacterial, and viral infections through drone and satellite platforms. Flow cytometry characterizes fungal and bacterial genome size and quantifies oomycete populations. Hyperspectral imaging, capturing hundreds of narrow bands, detects biochemical changes and pigment degradation before symptom expression, supporting pre-symptomatic detection of *Xylella fastidiosa*, *Blumeria graminis* f. sp. *hordei*, CMV, and *Sphaerotheca fuliginea*. Thermal imaging measures leaf temperature variations caused by infection-induced stomatal closure and reduced transpiration, aiding detection of *Pseudoperonospora cubensis*, wilt diseases, root rot, and separating drought from disease symptoms. Fluorescence imaging monitors chlorophyll fluorescence to reveal photosystem disruption and early stress in viral diseases, powdery mildew, necrotrophic pathogens, and Fusarium head blight. X-ray imaging is useful for detecting internal rots in fruits, seed infection, and stem damage, while MRI and CT scanning help identify internal tissue decay and root infections in soil. Microscopic imaging including light, fluorescence, confocal, and electron microscopy supports the detection of hyphae, spores, pathogen structures, host–pathogen interactions, and viral particles. Airborne imaging systems such as colour infrared (CIR) are used to map citrus Phytophthora foot rot, wheat yellow rust, and cotton root rot. Various imaging platforms like satellites for regional mapping, UAVs for field-level surveillance, tractor-mounted sensors for precision agriculture, and smartphones for quick diagnosis are increasingly used in plant disease detection.

- **Surveillance using satellite technology**

Satellite technology has transformed disease surveillance from field-scale monitoring to regional and national observation. Remote sensing satellites detect plant diseases by measuring changes in reflectance, temperature, moisture, and canopy physiology. Infection causes chlorophyll loss, tissue damage, reduced water content, stomatal closure, and canopy thinning, altering visible, NIR, SWIR, and thermal signatures. Satellite data support (i) early detection of viral chlorosis, rust, mildew, and leaf blight, (ii) diagnosis of water-stress-linked diseases such as Fusarium and Verticillium wilt and root rots, (iii) thermal detection of stomatal closure and increased leaf temperature in wilt diseases, (iv) disease mapping and spread monitoring for rust, late blight, and blast epidemics, and (v) large-scale surveillance for crop health, yield loss estimation, hotspot identification, precision agriculture, and targeted fungicide application. Airborne and satellite imagery during the growing season aids early detection and need-based disease management. Examples include the use of Landsat imagery for severe take-all mapping in wheat, Quick Bird for powdery mildew, leaf rust, and basal stem rot, WorldView-2 for huanglongbing detection, and SPOT-6 for multilocational mapping of powdery mildew (Yang, 2020). Open-source platforms like Google Earth support mapping and sharing of disease distribution through GIS. The CIMMYT GIS unit has developed Rust Mapper, a Google-Earth-based tool displaying wheat rust survey sites, including races like Ug99. The Plantix mobile app by PEAT automates disease diagnosis for farmers and provides management advice, while ICRISAT has developed a database of over 60,000 images across 30–60 crops with prescriptions for more than 200 crop diseases in collaboration with PEAT.

- **Specialized diagnostic tools for plant disease**

Other than traditional diagnostic tools several newer technologies have been adopted to facilitate need based specific or non-targeted or multiplex detection. Considering their working principle, detection accuracy, they can be easily categorized under 'specialized diagnostics' (Table 1).

Table 2. Specialized diagnostic techniques for plant disease detection

Diagnostic tools	Principle of working	Implementation
DUALEX optical leaf -clip sensor (Biosensor)	Decreased epidermal Favonol content as pre-symptomatic biomarker	Pre-symptomatic detection of *Pseudoperonospora cubensis*
Gas Chromatography	Analysis of specific volatile organic compounds (VOCs) released by the infected sample under stress	Pre-symptomatic detection of *Teratosphaeria nubilosa*in leaves of *Eucalyptus globulus*
Metagenomic Next Generation Sequencing (m NGS)	Comparison of the sequencing of extracts from symptomatic and healthy plant. Facilitates non-targeted detection.	Identification of the microbiome of wheat plants infected by *Zymoseptoria tritici*

Single Nucleotide Polymorphisms (SNPs) chip	DNA microarrays capable of testing genetic variation at many thousands of specific locations across the genome	Rapid diagnosis of stem rust races (*Puccinia graminis* f.sp. *tritici*)
Luminex® technology	Aids in multiplex diagnosis up to 500 targets in a single sample. Small paramagnetic beads coated with specific antibodies or oligonucleotides capture PCR products obtained from their genetic material.	Simultaneous identification of 22 *Phytophthora* species to clade or subclade level.

Emergency response system of plant biosecurity from plant diseases

Emergency response is a rapid, organized action taken immediately after detecting an exotic high-risk disease to contain, eradicate and prevent its spread before it becomes established. This protects agriculture, environment and minimizes crop loss. The first step is proper diagnosis, detection and laboratory confirmation of the pathogen, followed by official declaration and notification to NPPO, government agencies and international bodies (IPPC, trading partners). A rapid survey determines the infested area, level of spread, affected hosts and the delineation of infected, buffer and pest-free zones. Quarantine restrictions are imposed on movement of planting materials with roadblocks, checkpoints and restrictions on sale of host plants.

Control measures include uprooting and destruction of infected plants, spraying fungicides/bactericides/nematicides and removing alternate hosts. Farmers are informed about symptoms, reporting procedures and movement restrictions and may receive compensation for large-scale destruction. Evaluation of the response is done to strengthen future plans. Emergency preparedness depends on contingency plans, rapid diagnostic kits, trained teams and legal authority for enforcement.

Cultivar level plant biosecurity from plant diseases

Disease-resistant varieties (horizontal, vertical, polygenic, gene deployment, gene pyramiding, transgenic) act as biological barriers against pathogens. They prevent establishment, reduce pathogen multiplication, produce fewer spores, lower inoculum level and break the infection cycle. Resistant cultivars are particularly useful in border areas, high-risk zones and germplasm introduction sites to protect disease-free regions. They reduce dependence on chemicals, lessen environmental hazards and support emergency response by slowing or containing epidemic development.

Farm level plant biosecurity from plant diseases

Farm-level biosecurity includes practices within a farm to prevent entry, spread and build-up of diseases and reduce off-season survival. It is considered the last line of defence. Key components include use of healthy planting material (certified seeds, disease-free seedlings), field sanitation (removal of diseased plants, destruction of residues, cleaning tools), control of entry of people, vehicles and equipment, proper soil and water management, crop rotation with non-hosts, destruction of alternate hosts, disinfestation of tools, regular monitoring, early detection, immediate removal of infected plants, proper disposal and vector control.

Awareness and training in plant biosecurity from plant diseases

Biosecurity depends heavily on people's knowledge, vigilance and behaviour. Awareness programmes support early detection, prevent accidental spread, encourage quick reporting, promote safe farming and trade, reduce crop losses and strengthen national preparedness. They use posters, leaflets, visuals, radio/TV messages, social media, alerts, field days, demonstrations, school programmes and community meetings to reach farmers, traders, nursery owners, travellers and border officials.

Training is more technical and skill-oriented. Farmers learn disease recognition, hygiene and reporting; extension staff learn field diagnosis and sampling; technical staff learn diagnostics, ELISA, PCR and quarantine procedures; border personnel learn inspection and interception; rapid response teams learn containment, eradication and decontamination. Training covers identification of diseases, signs, life cycles, surveillance techniques, trapping, sampling, lab submission, diagnostics, quarantine inspection, disinfection and emergency response procedures. Training is continuous, updated with new diseases and strengthened with refresher courses and simulation exercises.

International cooperation for plant biosecurity from plant diseases

International cooperation is essential because plant diseases move across borders through trade, travel, climate change and natural pathways. Cooperation helps prevent transboundary introduction, harmonize quarantine and phytosanitary standards, share surveillance information, strengthen early-warning systems and support safe global trade. The IPPC, governed by FAO, develops ISPMs (ISPM 1, 2, 6, 7, 12, 15), coordinates phytosanitary certification, PRA and information exchange. FAO supports capacity building and emergency programs. WTO-SPS ensures that phytosanitary measures are science-based and not used as unjustified trade barriers.

RPPOs (APPPC, EPPO, NAPPO) coordinate regional surveillance, set regional standards and disseminate disease alerts. Areas of cooperation include information exchange, joint surveillance, PRA, coordinated emergency response, training, research collaboration and ensuring safe trade. TR4, UG99 and citrus greening are prominent examples requiring global cooperation. Benefits include safeguarding food security, reducing invasive spread, enhancing diagnostic and surveillance capacity and enabling rapid global response.

Research and preparedness for plant biosecurity from plant diseases

Research provides scientific knowledge for identifying emerging diseases, developing rapid diagnostics (PCR, ELISA, DNA barcoding), studying climate-driven disease spread, developing surveillance tools (remote sensing, GIS), understanding pathogen biology, improving PRA and modelling risks. It also supports development of resistant varieties and sustainable control measures.

Preparedness ensures readiness before outbreaks and includes surveillance systems, diagnostic capacity, national contingency plans, clear chain of command, rapid response teams, simulation drills, stockpiling pesticides and protective gear, and effective communication systems (hotlines, farmer alerts, digital platforms). Preparedness is supported by research through faster confirmation of outbreaks, modelling disease spread, designing containment zones and selecting control methods. Benefits include early detection, reduced impact, lower losses, stronger biosecurity and improved food security.

Risk management in plant biosecurity

Risk management uses PRA results to reduce the likelihood of disease entry, establishment and spread while still enabling trade.

- **Pathway identification:** Seeds, nursery plants, wood packaging, soil, passenger baggage and machinery are evaluated. If a pathogen is injurious, preventive measures are prescribed (e.g., China banning Pinus imports from several countries).
- **Management option evaluation:** NPPOs choose measures that are effective, feasible, economical and minimally trade-restrictive.

Phytosanitary measures

- **Pre-border:** Pre-entry clearance, disease-free seed production areas, seed certification, treatment (fumigation, hot water, pesticides) and import prohibition for high-risk pathogens.
- **Border:** Verification of documents, inspection, sampling/testing, quarantine detention and re-export/destruction of contaminated consignments.
- **Post-border:** Post-entry quarantine, regular surveillance, treatment of infested materials and eradication/containment of outbreaks.

Tools used in risk management

Technical tools: Heat/cold treatment, irradiation and fumigation; limited use of chemicals as they may mask symptoms.

Regulatory tools

- **Phytosanitary regulations:** Built on IPPC, WTO-SPS and CBD principles; include regulated plant trade, treatment requirements, ensuring low pathogen prevalence, dormant plant imports and seasonal restrictions.
- **Import permits:** Countries may use blacklist or whitelist approaches; applications supply important information.
- **Phytosanitary certificates:** Issued by NPPO to certify pest-free status and compliance of consignments. Used for seeds, planting materials, fruits, grains, timber and other plant products. They include exporter/importer details, plant names, quantity, origin, transport method, entry point and declarations.
- **Soil regulation:** Soil import is highly restricted due to its ability to harbour survival structures; only limited soil quantities are allowed in specific cases.

Biological and cultural tools: Crop rotation, sanitation, resistant varieties and biocontrol agents (*Trichoderma, Gliocladium, Pseudomonas, Bacillus*) work through competition, antibiosis, parasitism, ISR and enzyme production. Cultural practices adjust crop environment, break pathogen cycles and suppress disease establishment.

Seasonal/growth-stage specific shipping: Import restrictions based on dormancy or asynchronous climates reduce pathogen prevalence (e.g., New Zealand's requirements for Malus, Prunus, Vitis).

Conclusion

Phytopathogen invasion by breaching biosecurity barriers has become a global concern since the 1800s. Plant biosecurity is a multidisciplinary, interconnected approach where plant pathology contributes crucial strategies for preventing pathogen introduction and spread through improved detection tools and strong regulatory frameworks at every stage of trade. National and international collaboration enhances preparedness, prevents epidemics and protects agricultural economics from devastating plant diseases.

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