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REVIEW

Phytosanitary management of ICARDA's germplasm seed collections for safe movement and better future use

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Abstract

Germplasm exchange from international genebanks and breeding programs is vital for successful crop improvement programs. More than 10,000 different accessions of wheat, barley, lentil, faba bean, chickpea, grasspea, and pasture and forage crops are distributed by the International Center for Agricultural Research in the Dry Areas (ICARDA) every year to around 70 countries. New accessions are added to the germplasm collections in the Center's genebank and utilized in the breeding programs. Recent years have witnessed an increasing global concern about the loss of plant genetic resources because of conflicts, human pandemic diseases, extreme weather events, pest and disease outbreaks, and natural calamities such as earthquakes, floods, etc., which led to disrupting access to germplasm and undermining social protection systems. Safety duplication of germplasm collections held in genebanks in other institutions, including international, regional, and national genebanks, as well as the Svalbard Global Seed Vault (SGSV), is one of the essential measures to safeguard germplasm and also to replenish any lost accessions and resume use and distribution of seeds to users internationally. Germplasm distribution procedures are conducted per International Plant Protection Convention phytosanitary regulations to avoid the transboundary spread of seed-borne pests and pathogens. The ICARDA's Seed Health Laboratory exercises maximum efforts to maintain the "phytosanitary clean" health status of germplasm during regeneration, conservation, distribution and ensure compliance with phytosanitary regulations in international germplasm distributions to guarantee minimum loss of genetic resources. These efforts include the development of new methods to detect and manage seed-borne pathogens. An increase in global awareness to preserve germplasm for current and future use is crucial to combat climate challenge, malnutrition, and food insecurity.

Keywords: CGIAR, plant genetic resources, germplasm health, food security, disease detection, seed health testing, seed-borne diseases, pests and diseases

Review methodology

This review focuses mainly on the role of ICARDA's Seed Health Laboratory (SHL), part of the network of CGIAR Germplasm Health Units (GHUs), to ensure the movement of ICARDA germplasm for research and education. We have supplemented this review with our data. In addition, we reviewed pre-reviewed journals and websites for recent articles related to the article topic, many of which are cited in this review. We also used references from the articles obtained by these methods to find additional relevant information.

Background

The Consultative Group on International Agricultural Research (CGIAR) (Available at: www.cgiar.org, accessed 14 November 2023) is the world's largest global research partnership for a food-secure future dedicated to transforming food, land, and water systems in a climate crisis. CGIAR was established in 1971 and consists of 15 international research centers working under One CGIAR mandate to reduce rural poverty, increase food security, improve human health and nutrition, and sustainable management of natural resources (Alston *et al.*, 2020). CGIAR centers collaborate

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with partners from national and regional research institutes, civil society organizations, academia, and the private sector. Within the framework of the CGIAR, the International Center for Agricultural Research in the Dry Areas (ICARDA) has a global mandate of developing international public goods for lentil (*Lens culinaris* Medik.), faba bean (*Vicia faba* L.), and barley (*Hordeum vulgare* L.), targeting non-tropical dry areas. Moreover, ICARDA has the regional mandate of improving bread wheat (*Triticum aestivum* L.), durum wheat (*Triticum* durum L.), Kabuli chickpea (*Cicer arietinum* L.), pasture and forage legumes, and associated farming systems.

The development of improved germplasm for efficient use by national, regional, and international breeding programs is the major objective of the ICARDA crop improvement program. ICARDA holds “in trust” rich and valuable collections of genetic resources of cereals and food legumes and their wild relatives in its Genebanks located in Terbol-Lebanon and Rabat-Morocco. Based on CGIAR intellectual assets principles, the breeding germplasm developed by ICARDA, and all the genetic resources held in trust are considered international public goods (IPGs) to be made available upon request to national and international researchers, individuals from the private sector, graduate students, farmers, and others around the world for use in breeding, research, and education purposes. The exchange of breeding genotypes and genetic resources held at ICARDA is under the standard material transfer agreement (SMTA) adopted for exchanges of materials under the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA or the Plant Treaty) of the Food and Agriculture Organization (FAO) (Halewood *et al*., 2020). This agreement is compulsory to access the materials for conservation and use in research, breeding, and education. Facilitated seed and germplasm exchange and movement are vital for crop improvement, conservation, and use of genetic resources.

Approximately 10,000 different entries (genetic resources, breeding materials, international nurseries, diseases, and insect pest nurseries) are shared with ICARDA collaborators, mainly national agricultural research systems (NARS), universities, breeding stations, etc. Over 70 countries receive ICARDA’s germplasm annually through its international nursery platform and Genebank germplasm. In parallel, ICARDA also receives seeds of cultivated and wild relatives of crops from research institutions in more than 50 different countries. The quantities can vary from a few seeds of wild species to several kilograms of commercial varieties.

More than 1300 insect pests and pathogens threaten agricultural crops globally, with an estimated economic impact of around $540 billion annually (Paini *et al*., 2016; Key Report, 2017; Kumar *et al*., 2021). Emerging and introduced plant pathogens, insect pest, and parasitic weeds incursions in new areas affect food security, diet diversity, and human health, with serious economic implications for agriculture, food systems, and biodiversity (Anderson *et al*., 2004; Ristaino *et al*., 2021; Savary, 2023). Seed-borne pathogens represent a major threat to crop growth and productivity (Bos, 1977; Kumar and Gupta, 2020; Dell’Olmo *et al*., 2023).

Seed is a basic and critical input in agriculture to ensure global food security. Around 90% of the crops grown all over the world are propagated by seed. However, seeds are a means of transferring many pathogens and pests, including fungi, nematodes, bacteria, viruses, insects, and parasitic weeds, which may cause potential risks to the agriculture of the importing country (Chalam *et al*., 2020; Dell’Olmo *et al*., 2023). Germplasm transfers and exchanges have been recognized as an essential pathway for the transboundary spread of pests and pathogens through human collection and distribution activities (moving pests among geographies and introducing them into new regions where they did not exist before) (Bos, 1977; Elmer, 2001; Kumar *et al*., 2021). The spread of pests has increased dramatically in recent years, and in the coming decades, it is expected that shifts in the geographic distributions of pests and pathogens in response to climatic factors (e.g., wind, rainfall) and increased global commerce through the agricultural trade and unintentional movement of infected living materials (e.g., infected seeds, tissue culture materials, roots, bulbs, tubers) will make them both more frequent and severe (Anderson *et al*., 2004; Bebber *et al*., 2013, 2014; Bebber, 2015; Santini *et al*., 2018). In the last 200 years, many important pathogens have also been established far from the center of their origin (Kingsolver *et al*., 1983; Stace-Smith, 1985; Waterworth, 1993; Lozoya-Saldaña, 2001; Simler *et al*., 2019; Kumar *et al*., 2021).

Seed health testing is a first-line approach to the general strategy of plant disease control and covers many aspects: testing for seed certification, quarantine, and phytosanitary measures, production of healthy crops, evaluation of planting value, advice and effectiveness of seed treatment, storage quality, and cultivar resistance (Kumar and Gupta, 2020). Therefore, timely detection and diagnosis are prerequisites for effective management (Kumar and Gupta, 2020). To investigate seed health, several tests for different seed-borne pathogens are standardized by individual researchers and organizations (Kaur *et al*., 2020; Kumar *et al*., 2020; Singh and Rathaur, 2020; Singh *et al*., 2020). Neergaard (1977) made a great contribution to the development of seed pathology, and hence, he is considered the father of seed pathology. Many organizations, including CGIAR GHUs publish seed health testing procedures and standards. However, seed health testing methods, especially for orthodox seeds, published by the International Seed Testing Association (ISTA) (Available at: www.seedtest.org, accessed 14 November 2023), the International Seed Health Initiative (ISHI), and the USDA’s National Seed Health System (NSHS) (Goswami *et al*., 2020) are commonly used as benchmark methods. Among them, ISTA is a key institution that provides an internationally agreed set of rules for seed sampling and testing, gives authority to seed testing laboratories, and provides international seed analysis certificates to facilitate national and international seed trade (FAO and ISTA, 2023).

CGIAR centers as well as at other institutions, stored large germplasm collections under conditions favorable for maintaining seed viability over long periods. There is, however, a risk of having infected seeds that inadvertently could be spread to other countries. Different pathogens survive in or on seeds for various periods, ranging from a few months to several years in stored seeds (Neergaard, 1977). Without proper phytosanitary measures of international agencies, germplasm distribution increases the possibility of pest dissemination in areas previously considered to be disease-free (Stace-Smith, 1985; Khetarpal *et al*., 2001). Therefore, extreme care is required to ensure that the exchanged germplasm is pest-free, hence, the CGIAR centers have set up Germplasm Health Units (GHUs) [*GHU is named Seed Health Laboratory (SHL) or Seed Health Unit (SHU), in some CGIAR Centers*]. The main objectives of the GHUs (Seed Health Laboratories of the CGIAR centers) are: (i) averting the spread of quarantine pests with CGIAR germplasm transfers, (ii) preventing pest outbreaks, (iii) safeguarding biodiversity, and (iv) strengthening the development of phytosanitary capacities (Kumar *et al*., 2021). GHUs serve as the CGIAR centers’ gateway for germplasm exchange by ensuring compliance with the FAO International Plant Protection Convention (IPPC) procedures and the International Standards for Phytosanitary Measures (ISPMs) applied by National Plant Protection Organizations (NPPOs) to prevent the introduction and control the spread of pests along with plants or plant products (Lozoya-Saldaña, 2001; MacLeod *et al*., 2010; Kumar *et al*., 2021). ICARDA established the Seed Health Laboratory (SHL) in Lebanon and Morocco, where the genebank and crop breeding operate.

This article briefly describes the role of ICARDA’s GHU/SHL in preserving germplasm through conservation, seed regeneration, and materials that are shared with partners.

Importance of plant genetic resources

Preserving plant genetic resources is crucial for global food security and sustainability. Plant genetic resources provide valuable traits for developing resilient crop varieties and ensuring the adaptability of our food system to various stresses. Preserving these resources is an investment in a sustainable global future, empowering humanity to overcome challenges and secure abundant harvests for generations to come.

The FAO's Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture suggested that in 2010, there were 1750 individual genebanks around the world that collect, store, regenerate, and distribute landraces and their wild relatives. To date, there are 7.4 million accessions maintained in genebanks around the world, and roughly 25% of them are unique accessions which are maintained in national, regional, and international *ex situ* collection of crops diversity, while the rest are duplicates (FAO, 2010; Popova, 2018). Genebanks are vital to the future of people and more valuable than ordinary banks. If these collections are not maintained, they face the risk of being lost forever.

The biggest and most important holdings globally are managed by the 11 genebanks of CGIAR centers, which conserve 739,653 accessions of cereals, grain legumes, forages, tree species, root and tuber crops, and bananas (GBP Annual Report, 2021). These accessions represent 174 genera and over 1000 species obtained from 207 countries, which are conserved in 35 collections around the world as seed, *in vitro* material, and as living plants in the fields or screenhouses (Kumar *et al*., 2021). Many of these accessions are crop wild relatives. During 2021, a total of 96,590 germplasm samples (63,788 accessions) were distributed by CGIAR genebanks to users (universities or research institutes, National Agriculture Research Systems [NARS], commercial sector, NGOs, farmers, and individuals) in 91 countries (GBP Annual Report, 2021). ICARDA Genebanks holds around 157,000 accessions, 58% are landraces and crop wild relatives, 20% are forages and range species, and the remainder are breeding lines at various stages as well as released varieties (barley, bread, and durum wheat, faba bean, chickpea, lentil, grasspea, pea, forage, and range plants) (Westengen *et al*., 2020). Seed banks function as bank accounts for plant genes. Collectors deposit seeds, which can later be "withdrawn" to replenish crops lost in conflict or disaster, breed new traits into crops – such as pest or heat resistance – and research the evolution of plants over the ages. ICARDA's collection is especially valuable because it aims to collect seeds from the world's dry regions. It was previously held entirely at the Genebank in Aleppo-Syria, which was vacated in 2012 due to the Syrian war, and later two genebanks were established in Lebanon mainly for wild relatives and Morocco (cultivated species) to ensure the preservation of this valuable collection that contains many wild relatives of wheat, barley, lentils, and grass pea (Bhattacharya, 2016; Westengen *et al*., 2020; Mneimneh, 2021).

Safeguarding global crop diversity

Genebanks are exposed to manifold endogenous and exogenous threats that might jeopardize their physical integrity around the world (Herbold and Engels, 2023). These challenges can impact the activities and the missions of the genebanks and therefore have a long-term impact on the ability of countries to develop and implement sustainable agricultural practices. In recent years, there have been a number of cases of seed genebanks being damaged or destroyed due to many factors, such as the conflicts in Afghanistan, Burundi, Rwanda, and the Solomon Islands (Varma and Winslow, 2004; Gewin, 2015). When genebanks flooded in Thailand in 2011, some of the unique 20,000 rice accessions were lost forever (Gewin, 2015). The national genebank of the Philippines at Los Baños was damaged by flooding due to a typhoon in 2006 and hit again by a fire in 2012 (Gewin, 2015; Fu, 2017). Ukraine's seed bank in Kharkiv was at high risk as the city has been a staging ground for military operations in February 2022 (Angel, 2022). In a consolidated effort, the collection was relocated in 2023 (FAO, 2023). When war broke out in Syria in 2011, the future of one of the world's most important Genebank was put at risk. What followed was an internationally coordinated rescue to ensure the preservation of this priceless heritage (Westengen *et al*., 2020). Efforts are being made at the global level to address the genebank crisis. These efforts aim to ensure the continued availability of plant genetic resources for sustainable agriculture and food security, even in the face of the challenges posed by the genebank crisis. Dr Cary Fowler (former executive director of the Global Crop Diversity Trust, the Bonn, Germany-based international body with the mission of safeguarding crop diversity forever) says that "at any *given time, there is almost always something bad going on in one of the genebanks around the world"* (Gewin, 2015). This vulnerability inspired Fowler to champion the creation of the Svalbard seed bank, a so-called "doomsday vault" inside a permafrost-encased Norwegian mountain, to serve as a global backup for the world's seed collections. The Svalbard Global Seed Vault (SGSV) purpose is to backup genebank collections to secure the foundation of our future food supply. It holds duplicates of 1,255,332 seed samples representing 6120 species of 99 genbanks from almost every country around the world, with room for millions more (October 2023; www.seedvault.no, accessed 14 November 2023). But unlike ICARDA and other genebanks, Svalbard is simply an icebound warehouse, not a working entity able to contribute genetic diversity to global breeding efforts.

As per the FAO Genebank Standards for Plant Genetic Resources for Food and Agriculture (FAO, 2014), most genebanks should have safety duplication conservations in the SGSV and/or in third-party countries i.e., in one or more institutions, including international, regional, and national genebanks. Preferably, the black box agreements are applied where the recipient institution conserves the duplicate but has neither rights over it nor further obligations (i.e., is not responsible for viability testing and is not allowed to regenerate, use, or distribute the material if not authorized by the depositor). Of the CGIAR seed accessions, 88% are duplicated at the SGSV, and 71% are safely duplicated in two locations. A total of 70% of clonal crop collections are safely duplicated in the form of cryopreserved or *in vitro* cultures (GBP Annual Report, 2021).

Seed-borne pathogens and insect pests

Germplasm is generally obtained or collected from different geographical regions, and many accessions are multiplied in a relatively small area at the research or plant introduction station. If only one line is infected with an exotic pathogen, and conditions are favorable for disease development, it is likely that a large number of susceptible accessions will also become infected. Another reason for reports of exotic pathogens occurring at plant introduction stations could be that at least in some countries plant pathologists focus their attention on research stations rather than on farmers' fields and thus disease outbreaks are more readily detected in these stations (Plucknett and Smith, 1989).

Collecting germplasm can also result in collecting pathogens, and with the movement of germplasm, there is a risk of spreading pathogens or their races to new areas where they did not occur before, which could spell significant crop losses. Undoubtedly in the centers of genetic diversity of germplasm, there is also a diversity of pathogens and their races. From a quarantine point of view, the race question is very important, too. Many pathogens occur in different races, which are morphologically identical but differ in their virulence and host range. The problems with crop resistance breaking down upon the introduction of new races are very real and can be catastrophic.

In the context of seed health, seeds have been recognized as an important pathway for the spread of pests and pathogens. Seed-borne pests and pathogens reduce storage longevity and cause poor germination or field establishment in addition to disease development in the field that leads to reducing the value of the crop. A considerable number of pathogens are disseminated by seeds. Richardson (1979, 1981, 1983) listed some 500 different plant species that are attacked by more than 1300 different pathogens; many of these pathogens can attack more than one plant species. Probably only very few plant species are not hosts for one or more pathogens. Around 80% of the seed-transmitted diseases are caused by fungi. The remaining 20% of pathogens are viruses – and possibly viroids, bacteria, and nematodes. Hull (2014) indicated that about one-quarter of the reported plant viruses are transmitted through seeds. Since viruses can survive for a long time in seeds, seed-borne viruses can spread over large distances (Hull, 2014). There are a number of quarantine risks (insect pests, pathogens, nematodes, parasitic weeds) associated with the movement of food legumes, cereals, forages, and rangelands germplasm (Kumari *et al*., 2022c; Dell'Olmo *et al*., 2023).

Infestation with storage insect pests is observed only occasionally in stored germplasm since the standard storage conditions are unfavorable for their development. Insect infestation of seeds is easily detectable compared to infection or contamination with pathogens. However, germplasm is not in all cases stored under ideal conditions, and therefore, insect pests also deserve attention.

Unfortunately, there are many examples where pathogens survive even under the recommended storage conditions (Neergaard, 1977). Some pathogens survive for more than 10 years. Generally, one could expect at least a low percentage of the inoculum to survive as long as the seeds. Such infection may not alarm plant breeders and may be perfectly acceptable for seed production if the rate of disease development is low. In some pests, zero tolerance is implanted to protect the crop. However, to minimize the risk of spreading pathogens, a very low incidence of seed-borne inoculum warrants attention.

Mission and tasks of ICARDA's seed health laboratory

ICARDA Genetic Resources Unit is responsible for germplasm collection, rejuvenation, conservation, documentation, and distribution. New accessions are added annually, either from joint collection missions or from researchers and partners inside and outside ICARDA. Within its routine genebank activities, all accessions are conserved in active and base collections and for safety duplication. Moreover, all samples to be distributed or acquired are cleaned of quarantine seed-borne pests. These accessions are also tested and cleaned after each cycle of multiplication. Seed health test results are included in the genebank database, and the information is used for further distribution of seeds from the genebank without additional testing. The International Nursery (IN) platform at ICARDA is responsible for seed production and distribution of elite breeding to partners. All seeds from IN are tested by SHL to quarantine pests to safeguard partners from pest introduction.

ICARDA's SHL in Lebanon and Morocco tests annually around 50,000 seed samples and provides clearance and documentation of safe germplasm movement. All incoming and outgoing genetic resources and breeding lines must go through a strict quarantine monitoring system (seed health testing and quarantine clearance based on national and international norms and procedures). ICARDA-SHL collaborates with the quarantine services of the host countries in Lebanon and Morocco, where ICARDA has breeding and genetic resource conservation activities, to ensure safe movement of seeds and avoid any breaches of the host and receiving countries' quarantine protocols (Fig. 1). To safeguard countries from quarantine pest risks associated with the germplasm movement, ICARDA follows a regulatory and quarantine program working in close collaboration with competent institutions where ICARDA has platforms for crop breeding, germplasm multiplication, and evaluation and genetic resources.

ICARDA's SHL applies specific procedures that are used to eliminate pests, including the use of seed treatment and fumigation procedures for the regeneration and harvesting of seed from healthy plants. The testing process covers all the pests and pathogens listed in the quarantine regulations of the recipient countries as well as the hosting countries (Lebanon and Morocco) under a comprehensive quality management system (QMS) based on the IPPC and respective policies of the NPPOs of all involved countries (Kumar *et al*., 2021). Thus, specific flowcharts for the protocols are assigned for incoming (import) and outgoing (export) germplasm separately (Figs. 2 and 3). This includes testing the transferred seeds for storage pests, fungi, bacteria, viruses, nematodes, and parasite weed seeds, this protocol is applied for all ICARDA mandate crops. Another task presented is to inspect the isolation area or post-entry quarantine isolation areas (PEQIA) (where the imported seeds are being increased and inspect the fields and/or greenhouse areas) (Niane *et al*., 2016). All these protocols and procedures aim to make sure that only seed samples that satisfy international phytosanitary standards are allowed for shipping.

The quarantine monitoring and clearance procedures for the outgoing seeds produced by ICARDA start with field inspections at different crop growth stages (Fig. 2) to check freedom from impurities, namely plant weeds, and from seed-borne diseases, such as Ascochyta blight, Fusarium wilt, Botrytis mold, nematodes, Bean

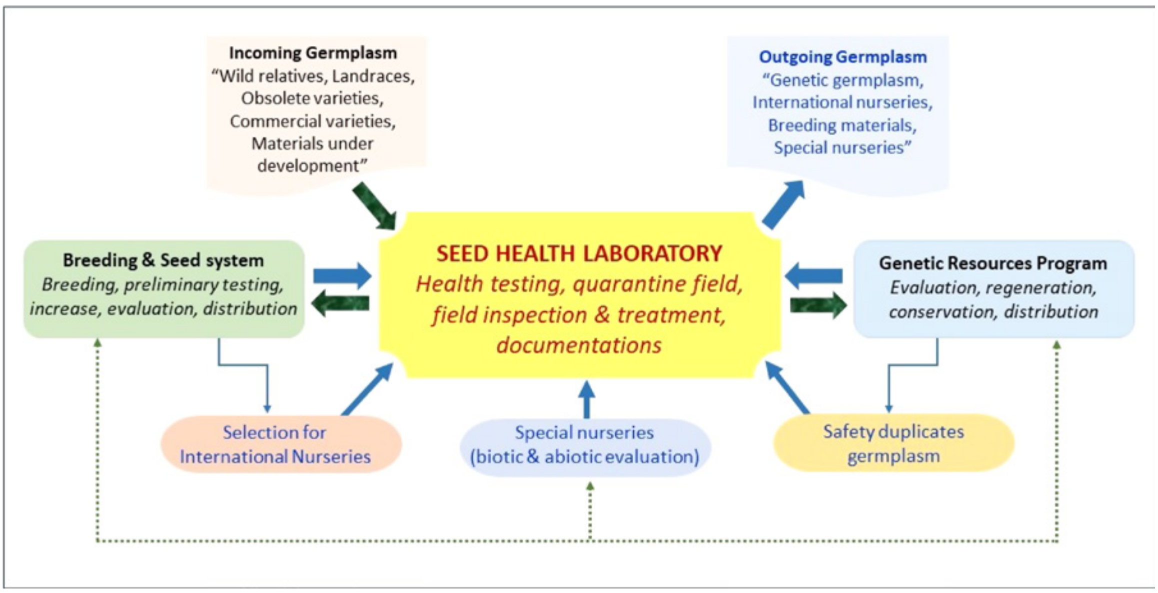

Fig. 1. ICARDA Seed Health Laboratory (SHL) role in relation to movement of genetic resources and breeding lines.

yellow mosaic virus, Broad bean stain virus, *Orobanche*, *Cuscuta* spp. (food legume crops), common bunt, loose smut, flag smut, dwarf bunt, Ergot, Fusarium head blight, black point (cereal crops), bacterial blights, aphids, and abiotic stress symptoms. Figure 4 shows a few symptoms of seed-borne diseases of legume and cereal crops that can be observed during field inspection. All field inspections must be made by well-trained and qualified personnel. The inspector has to know the prerequisites and standards for seed growing and should be familiar with the seed-borne disease symptoms and growth characteristics of the crop varieties to be inspected. The prescribed procedures and techniques of field inspection and the minimum number of inspections specified in the certification standards should be strictly adhered to. This is followed by seed sampling and testing based on the requirements of host and recipient countries and on international seed health testing norms and standards. After rigorous field inspection and a comprehensive review of seed health test results, a phytosanitary certificate is issued by the quarantine authorities of the respective host countries (Lebanon and Morocco). All quarantine monitoring and clearance procedures are fully documented. This documentation includes germplasm dispatch request proforma, phytosanitary certificate, certificates of donation, GMO-free certificates, commercial invoices, and certificates of origin for distributed seeds (Fig. 2).

The process of importation is initiated by the documentation stage to issue the import permit from NPPOs in the host countries (Fig. 3). Seeds cleared from the customs and quarantine services of ICARDA host countries are directly received by SHL, fumigated, and then subjected to appropriate visual and laboratory examinations (Kumari *et al*., 2022a, b). If pest(s) are detected, appropriate eradication treatments, such as seed cleaning by washing, heat

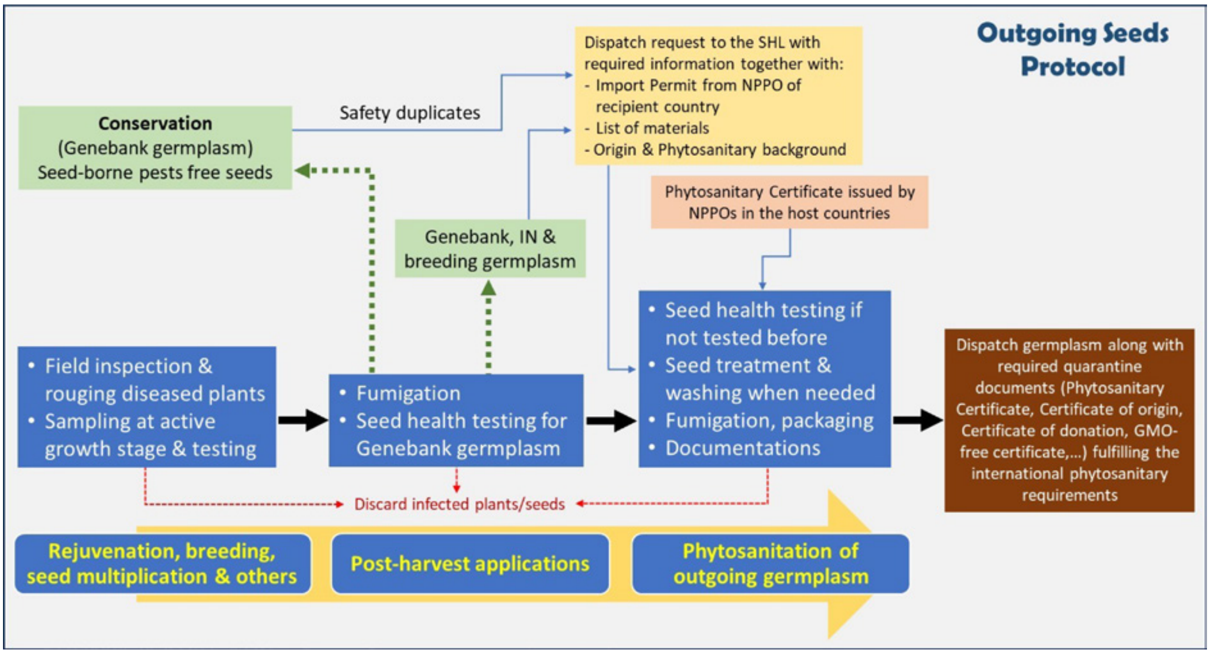

Fig. 2. Protocol of outgoing seeds applied by ICARDA's Seed Health Laboratory (SHL) in Lebanon and Morocco.

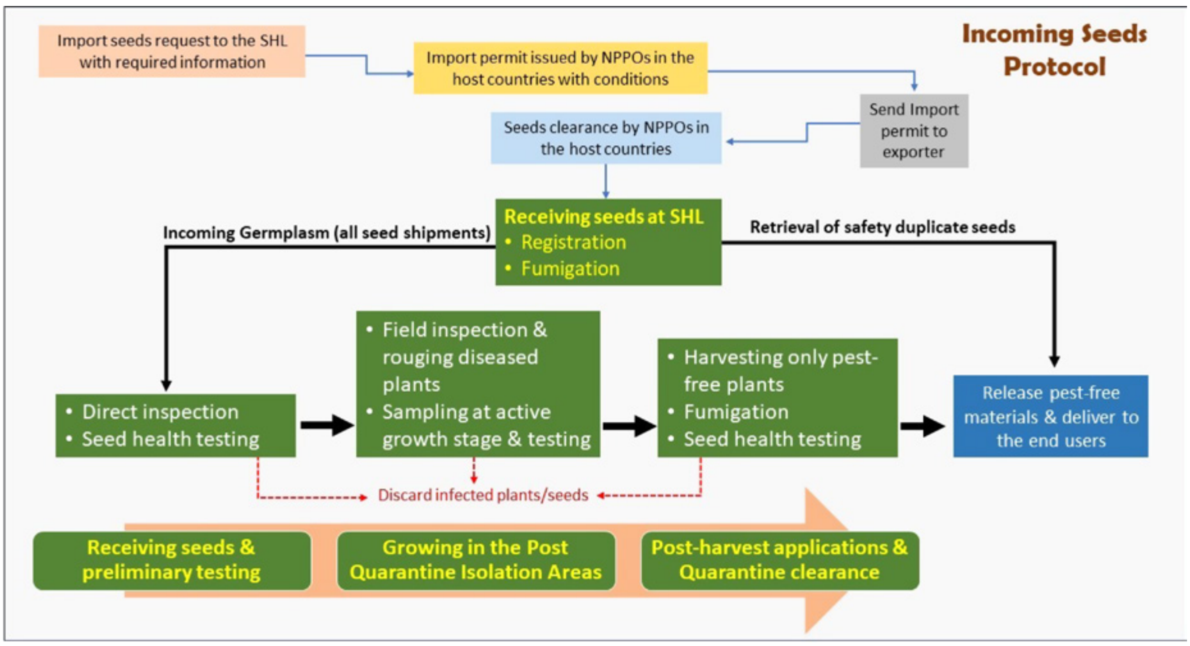

Fig. 3. Protocol of incoming seeds applied by ICARDA's Seed Health Laboratory (SHL) in Lebanon and Morocco.

Fig. 4. Symptoms of seed-borne pathogens affecting legume and cereal crops observed during field inspections.

treatment, or chemical dressing, are applied before the release of the materials for sowing. Seeds that are released after laboratory testing are then planted without exception in the PEQIA (Niane *et al*., 2016). The PEQIAs are dedicated to monitoring, detecting, and destroying any entry with quarantine pathogens that may have not been detected by laboratory tests. Plants in the post-quarantine areas that show unusual symptoms will be excluded, moved to SHL for infection determination and confirmation, followed by elimination in case of infection by autoclaving at 121°C, 15 psi for 15–20 min, and buried out in designated areas at the ICARDA premises after acknowledging the concerned breeder.

ICARDA's SHL played an essential role to facilitate safety retrieval of duplicates from depositing location to Lebanon and Morocco in collaboration with the NPPOs to comply with phytosanitary regulations in both countries. The role of SHL is still continuous as these duplicates should be sent back again to the SGSV after multiplication, thus, SHL applies the protocols and procedures of outgoing seeds on these materials in order to make sure that germplasm is decontaminated and free from seed-borne pathogens and pests. Moreover, SHL arranges for the proper documentation, packaging, and shipping to guarantee that the deposited materials are perfectly processed and packaged to minimize any potential damage during transportation and storage (Fig. 3). This basically aims to facilitate the direct, flexible, and regulated access and safe delivery of duplicates to the new destinations in case of partial or total loss caused by natural or man-made catastrophes. For this reason, ICARDA SHL is considered as a critical component of the safety duplication process and plays a vital role in ensuring the safety and security of the duplicate seed collections stored in the SGSV. This is important for protecting plant genetic diversity and to ensure its availability for future generations.

The CGIAR GHUs routinely check for about 320 pests that are endemic in germplasm production sites, including bacteria, fungi, insects, nematodes, oomycetes, phytoplasmas, viruses, and viroids (See Supplementary Table S2 of Kumar *et al*., 2021). In 2021, the GHUs tested 213,164 samples for over 100 different seed-borne pests and pathogens, and just over half of these were for conservation in genebanks. Around 1600 germplasm exchanges with 126 countries were facilitated, involving the removal of nearly 8% of imported or exported samples because of infection with pests or diseases (GBP Annual Report, 2021). ICARDA SHLs in Lebanon and Morocco tested 48,404 samples in 2021 and the results were collected from 567,975 diagnostic reactions (GBP Annual Report, 2021).

In the years from 2018 till 2022, ICARDA's SHL facilitated about 1487 consignments that were distributed to 93 countries and 359 consignments were received from 28 countries in Lebanon and Morocco. Most of the distributions were to NARS partners, universities and national genebanks (Fig. 5). This onerous task

Fig. 5. ICARDA germplasm consignments (number of shipments) that passed through ICARDA's Seed Health Laboratory in Lebanon and Morocco from 2018 to 2022 for incoming and outgoing seed shipments. The intensity of the blue shade indicates the number of transfer instances.

involves the production and extensive seed testing to ascertain the health status of germplasm released to end-users to comply with plant quarantine regulations. Specifically, ICARDA's SHL tested and removed 0.4% of the 278,217 genebank samples, including those for import, export, and conservation, and 0.8% of the 228,452 breeding samples for import and export, were found to be infected with pests (Fig. 6). In this process, a total of 3,356,002 diagnostic reactions were employed to test 506,669 samples in these years.

Conclusions

During the Syrian war, ICARDA lost only 1.1% of the germplasm (1657 accessions) (ICARDA, 2020) due to the flexible and rapid access to the safety duplicates that were deposited and retrieved under the supervision of ICARDA's SHL. This is an important, positive story of collaboration between national and international genebanks working together to protect a unique global resource that we could not have possibly replaced if it had been lost. Maintaining plant health during germplasm regeneration, multiplication, and safe duplications is essential to reduce the risk of seed-borne pathogens spread via future germplasm distribution. Finally, ICARDA GHU/SHL efforts are an important step in providing effective implementation of safe movement of seeds, which in turn helps in maintaining crops sustainability and diversity.

The necessity of exchanging genetic material for crop improvement comes with the inherent risk of spreading pests and pathogens, or their variants to unaffected regions. To mitigate this risk, it is possible to implement various seed health precautions (such as field inspections, seed health assessments, and the application of seed treatments). Implementing a combination of these measures can significantly reduce the potential transmission of pests and pathogens. It is essential to recognize that achieving 100% safety against pathogen introduction may not be feasible. Therefore, enhancing collaboration between phytosanitary organizations and germplasm suppliers, along with improving diagnostic tools, is highly desirable to better control the spread of pests and pathogens alongside germplasm.

Several economically important pest outbreaks in the last decade were attributed to introduced pests. One of the challenges to ICARDA SHL's services includes emerging new pests and the risk perception of invasive pests spreading into host countries. To cope with all emergencies, ICARDA's SHL attempts to adopt/validate new methods and techniques for germplasm phytosanitation and adopt more accurate and rapid detection of existing and newly diagnosed pests and pathogens to assure that the adapted methods offer cost and time efficiency, meet regulatory requirements, and comply with QMS systems (Kumari and Moukahel, 2022a, b). ICARDA's SHL dedicates intensive effort toward developing new nucleic acids-based detection protocols for identifying several pathogens that are difficult to detect through conventional tests.

As part of the QMS, seven standard operating procedures (SOPs) have been developed, unified and harmonized in the two locations (Lebanon and Morocco), which are audited and validated through internal and external expert review. This should fuel fruitful collaborations with the NPPOs and IPPC and contribute to the much-needed updating of the lists of quarantine pests and pathogens of ICARDA mandate crops. General procedures for testing, detection, diagnosis, and seed treatment for the elimination of seed-borne pests are used (Aveling, 2014), including the ISTA methods, where applicable (ISTA, 2023).

Comprehensive lists of seed-borne pests and pathogens specific to individual countries should be made available for use by quarantine services. The adoption of a Plant Germplasm Health Certificate, as recommended by the FAO/IBPGR Task Force on safe germplasm transfer (Hewitt and Chiarappa, 1977; Kumar *et al.*, 2021), would provide additional information about the test results and any other measures, such field inspections or meristem culture multiplication, carried out in the country of origin.

It is crucial to give serious consideration to the risk of introducing pests and pathogens or their variants, while also recognizing the benefits of broadening the genetic diversity of crop plants. When assessing this risk, it is essential to acknowledge that the mere

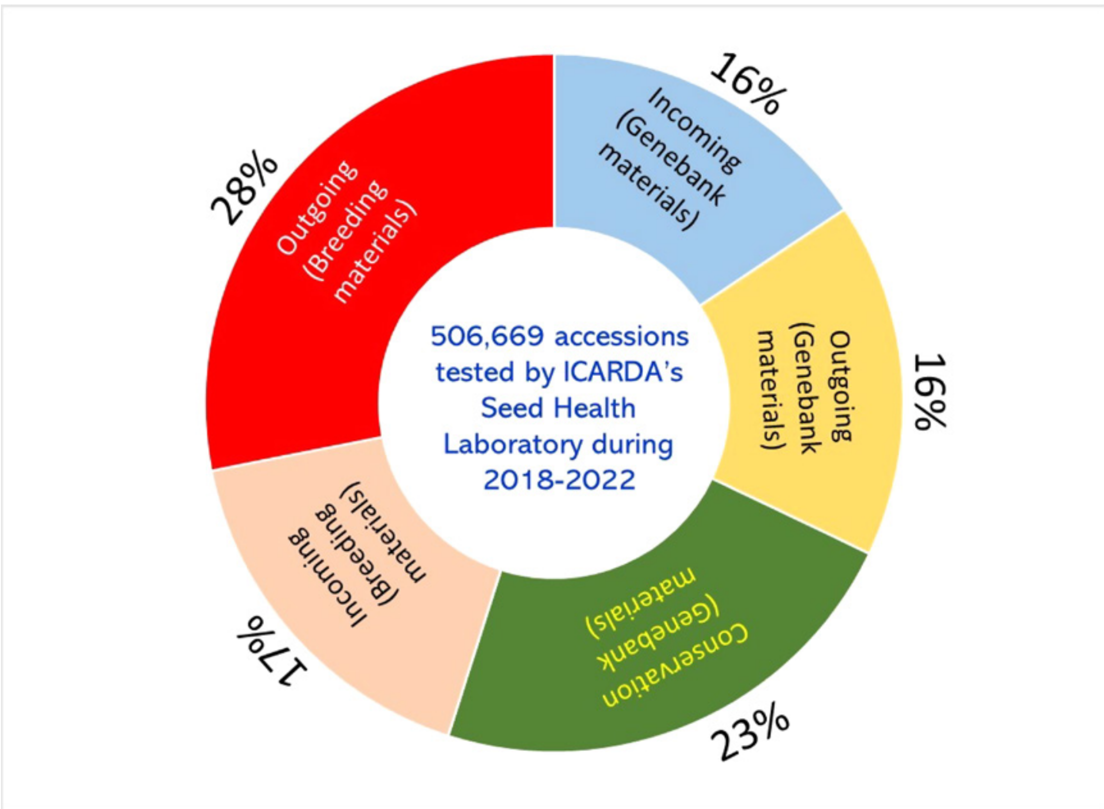

Fig. 6. Percentage of ICARDA's Seed Health Laboratory services for the genebank and breeding programs at ICARDA, 2018–2022 in Lebanon and Morocco.

spread of a pathogen does not guarantee the transmission of a disease. The outbreak of a disease depends largely on favorable environmental conditions, which are not always known in recipient countries. Consequently, ICARDA has adopted reasonable and effective precautionary measures to ensure that pathogen-tested germplasm is distributed from its research station and accepted in a responsible manner.

ICARDA's SHL is operating, under system support, the use of well-standardized procedures and protocols in harmony with NEPPOs regulations and ICPP procedures to keep up-to-date, effective, and reliable system to be stand by for any sudden unexpected scenarios such as changes in plant pests dynamics. Thus, ICARDA's SHL is trying to adopt a new online system to automate seed health services that are necessary to facilitate the processing of materials, which would notably improve the traceability of the process and real-time data collection and analyses. In parallel, ICARDA's SHL is conducting research relative to the seed testing domain and trying to continuously identify and try new and safe ingredients for crop protection and seed treatments, as some fungicides and insecticide treatments are banned or restricted for use on specific crops in some countries.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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