

Economical and Epidemiological Consequences of Seed Transmitted Plant Viruses. Review

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Abstract
Plant virus diseases greatly influence man's economy by reducing the yield and quality of plant products. About one-quarter of the known plant viruses are transmitted through the seed. Seed transmission of plant viruses is an important means for the introduction of plant viruses into new localities where they may become established, spread rapidly, and can cause epidemics in the presence of suitable vectors and host species. Viruses may persist in seed for long periods so that commercial distribution of a seed-borne virus over long distances may occur. The location of the virus in seed determines the transmissibility of viruses through seed. The virus is considered to be externally seed transmitted when it is outside the functional seed and internally seed transmitted when it is within the tissue of the seed. Seed infection by the virus is epidemiologically important for the reason that it is the primary source of inoculums and forms the starting point for the initiation of the disease. Avoidance of virus inoculum from infected seeds; chemical seed disinfection, implementing the cultural practices like field sanitation, rouging, and crop rotation can reduce the virus disease incidence. The role of quarantines, resistant cultivars, healthy seed production, and certification schemes for healthy seed production are also critical measures for seed transmitted virus management.
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1. Introduction

The seed is a productive propagule to be responsible for the species that germinate to produce a new plant. About 90% of food crops grown are propagated through seed. However, seeds, from the time of their inception at the flowering of the parent plants until their germination and development into seedlings can infected by different pests and known to be the most efficient vehicles of transport for a number of plant pathogens including fungi, bacteria, and viruses (Sastry, 2013). Plant virus diseases significantly influence man's economy by reducing the yield and quality of plant products. Generally, though it is very problematic to enumerate a clear figure on the financial impact of plant viruses in agriculture, the loss estimated globally at greater than US$30 billion annually (Sastry and Zitter, 2014).

2. Economic Significance of Seed Transmitted Plant Virus

About one-seventh or more than 231 plant viruses have been reported to be seed transmitted in different food, fiber, ornamental crops and weed (Hull, 2002; King *et al*., 2011; Sastry, 2013), and the number is increasing from time to time.

The seed infected by virus may result in loss in germination/germination percentage get reduced; development of plant diseases; distribution of the virus to new areas and may causes from low to high yield reduction (Table 1). Losses are generally greatest when plants become infected at vulnerable early growth stages and incidence approaches 100%. Estimation of losses based on yield comparisons between plots of inoculated and uninoculated plants mostly represents only the maximum loss caused by the virus, even 100% infection takes place under natural conditions (Irwin *et al*., 2000; Ruesink and Irwin, 2006; Wangai *et al*., 2012).

Table 1 Some examples of yield loss caused by seed transmitted viruses

Crop	Virus	Yield loss (%)	Reference
Bean	*Bean common mosaic virus*	50-68	Hampton,1975
Peanut	*Peanut mottle virus*	31-47	Kuhn *et al*., 1978
Peanut	*Peanut stunt virus*	80	Culp and Troutma, 1967
Peanut	*Peanut stripe virus*	21-23	Demski *et al*., 1984
Cowpea	*Cowpea mosaic virus*	13–87	Kaiser and Mossahebi, 1975
Cowpea	*Cowpea mosaic virus*	64–75	Suarez and Gonzalez, 1983
Cowpea	*Cowpea mosaic virus*	14	Pio-Riberio *et al*., 1978
Cowpea	*Cowpea banding mosaic virus*	11.5–43.5	Sharma and Varma, 1981
Cowpea	*Cucumber mosaic virus*	14	Pio-Riberio *et al*., 1978
Lentil	*Pea seed-borne virus*	96	Coutts *et al*., 2008
Barley	*Barley stripe mosaic virus*	62	Catherall, 1972

Virus infection causes not only quantitative loss of the harvested product but qualitatively for market value and nutritive composition. Loss of seed quality infected by viruses including discoloration and shriveling as a result the market level get reduced. For instance, *Pea seed-borne mosaic virus* makes necrotic rings and line patterns, cracking, and malformation in seed coats of pea, faba bean, lentil, and chickpea (Coutts *et al*., 2008; Latham and Jones, 2001). Similarly, *Broad bean stain virus* infection results undesirable staining of faba bean seed coats, which make the seeds less valuable for canning (Bos *et al*., 1988). The following figure (Fig. 1) indicate some examples that show types of symptoms and damage on seed due to seed transmitted viruses (Makkouk *et al*., 2014).

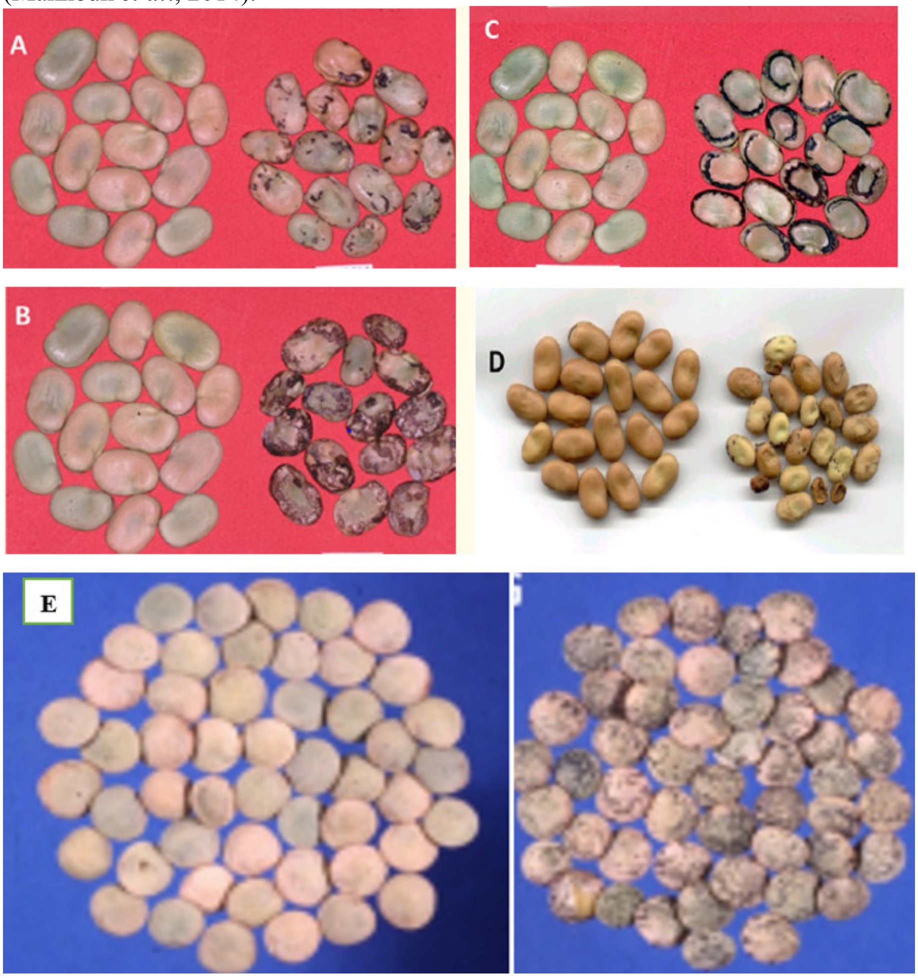

Figure 1. Symptoms and seed damage by seed transmitted viruses, virus-infected (right) and healthy (left): A= necrosis, reduction in size, and malformation in seeds of faba bean by *Bean yellow mosaic virus,* B= *Broad bean mottle virus,* C= *Broad bean stain virus,* D= Symptoms of malformation, reduction in size and necrotic rings caused by *Pea seed-borne mosaic virus* in faba bean seeds, E= Symptoms of necrosis in lentil seeds caused by *Broad bean stain virus.*

3. Type of seed transmission

The location of the virus found in seed determines transmissibility of virus through seed. Two general types of seed transmission can be distinguished (Hull, 2002).

i. **External:** The virus is considered to be externally seed transmitted when it is outside the functional seed. During germination, the virus infection takes place through the tiny abrasions caused by small soil particles. Huttings and Rast (1995) have reported that *Tomato mosaic virus* in tomato seed is localized on seed coat and sometimes in the endosperm. When externally seed transmitted, the virus is restricted to the testa as a contaminant. For example, *Tobacco mosaic virus* in tomato, seed transmission is largely due to contamination of the seedling by mechanical means. In the case of seeds from fleshy fruits like tomato, cucumber, watermelon and apple, viruses such as *Tobacco mosaic virus, Tomato mosaic virus, Potato virus X,* adhere to the seed coat (Sastry, 2013). The external virus can be readily inactivated by certain treatments eliminating all, or almost all, seed-borne infection.
ii. **Internal:** The virus is internally transmitted when it is within the tissue of the seed and is common type of

seed transmission, the virus is found within the tissues of the embryo. The developing embryo can become infected either prior to fertilization by infection of the gametes or by direct invasion after fertilization (Johansen *et al*., 1994). Some examples of internally seed transmitted viruses are *Bean common mosaic virus, Pea seed-borne mosaic virus, Barley stripe mosaic virus, Tobacco ringspot virus, Soybean mosaic virus* in soyabean*, Southern bean mosaic virus, Lettuce mosaic virus, Panicum mosaic virus, Pea early browning virus* and *Cucumber mosaic virus* (Sastry 2013). Each virus has been detected internally in cotyledons and embryos of their respective hosts (Roberts *et al*., 2003; O'keefe *et al*., 2007; Ali and Kobayashi, 2010).

4. Epidemiology and Factors Affecting the Proportion of Virus Infected Seed

A number of seed-transmitted virus diseases occur in the majority of crop plants cultivated under different environmental conditions. The epidemics of these virus diseases in a particular area are the consequence of complex interactions between different physical, chemical and biological factors, and major epidemics take place when conditions influencing the virus, host and its vector synchronize. The epidemiology of seed-transmitted plant viruses like in any other pathogenic diseases depends on the interaction of host (plant), pathogen (virus), vector, and the environmental conditions (Sastry, 2013). For viruses that also transmitted by vectors, even low rate of seed transmission can be epidemiologically important because this is the primary source of inoculum, forms the starting point for the initiation of the disease and ensures virus association with the planted crop and means for long-distance dissemination. As the infected seeds by the virus are randomly disseminated in the field, the infected dispersed seedlings aid as sources of inoculum for secondary spread by insect vectors (Sastry, 2013; Regassa *et al*., 2021).

4.1. Host plant

New crops have been introduced for the first time in new regions for their high yields and crop uniformity. These introductions will flourish in the new environment, where they will be free for some time from virus diseases that were prevalent in the country of origin. In other instances, catastrophic losses have occurred when exotic crops were soon attacked by indigenous pathogens not previously encountered in the country of origin. For example, when 'Fasolt', a hybrid cultivar of Brussel bread from Holland was introduced into England, it was severely affected by *Turnip mosaic* and *Cauliflower mosaic viruses* (Tomlinson and Ward, 1981).

The host plants and the type of vector involved also influence the efficiency of virus transmission as in the case observed by Jansen and Staples (1970) with beetle-transmitted *Cowpea severe mosaic virus.* Both cowpea and soybean are susceptible when mechanically inoculated. Beetles, however, transmitted this virus from cowpea to cowpea at high levels of efficiency but at a very low level to soybean. *Cowpea severe mosaic virus* was observed causing very severe disease in soybeans in the fields (Anjos and Lin, 1984).

Seed-transmitted viruses has been recorded both in annual and perennial crops. Annual crops are highly susceptible to viruses if extensively cultivated with high rate of seed infection, and vector presence results in maximum disease incidence and loss (Sastry, 2013).

Different varieties of the same host species often vary widely in the rate at which seed transmission of a particular virus occurs. For example, Zhang *et al*. (2011) reported that the rate of seed transmission of *Maize chlorotic mottle virus* (MCMV) was 2 seeds in 600 (0.33%) in a Chinese maize sample, however Quito-Avila *et al*. (2016) reported a considerably higher-level rate (8% and 12%) of MCMV seed transmission. In Ethiopia, the mean overall MCMV seed to seedling transmission rate of 20 maize genotypes was 0.073% whereas it ranged from 0 to 0.17% for the different varieties (Regassa *et al*., 2021). Seed transmission rates reported for *Barley stripe mosaic virus* in different barley cultivars vary from 0% to 75% (Carroll and Chapman, 1970).

Among the seed-transmitted viruses, some have limited host range like *Soybean mosaic virus*, and others have a wide host range (Irwin and Goodman, 1981). Similarly, *Bean common mosaic virus* and *Lettuce mosaic virus* infected seedlings raised from the seed are considered to be the primary source for initiating new infections at the beginning of each season. These viruses spread to other plants through vectors, and plants will subsequently act as secondary sources of infection depending on their susceptibility. In contrast, some seed-transmitted viruses of cucumovirus, tobravirus and nepovirus groups have a very large number of natural and experimental hosts comprising of annuals and perennials. For example, *Cucumber mosaic virus* can infect over 470 species of at least 67 families (Kaper and Waterworth, 1981). About 237 members of *Gramineae* have been shown as experimental hosts of various strains of *Barley stripe mosaic virus* (Jackson and Lane, 1981). Wherever the virus has a wide host range, the source of virus inoculum was necessarily another crop plant. For example, in Southern USA, peanut infected with *Pea mosaic virus* serves as a source of infection and also spreads to nearby soybean crop (Demski and Kuhn, 1974) and infected lupins after peanut crop (Demski *et al*., 1983).

Under field conditions, the weed and wild hosts are important as they are the reservoirs for the virus, vector or both (Regassa *et al*., 2020, 2021); aid in virus perpetuation during the main or off season; serve as inoculum source; and exert great infection pressure. Infected perennial weeds are more dangerous than annuals since they live longer. The chances of outbreak of disease epidemics will be more in areas where infected weeds are abundant and support the multiplication of a particular vector (Regassa et al., 2020). The importance of source of virus near or especially within a crop has been confirmed for many virus–crop combinations (Jones, 2004; Maramorosch *et al*., 2006; Regassa et al., 2021).

Within plantations, the infected weeds are particularly important since they exert the greatest infection pressure. Biennial or perennial weeds play a significant role in facilitating the survival of viruses that attack annual plants in areas with growing seasons restricted by prolonged drought or cold. Examples of weed hosts as reservoirs of seed-transmitted viruses are many. *Cucumber mosaic virus* also overwintered on weeds like *Echinocystis* sp. (9–55%) (Doolittle and Gilbert, 1919). In Australia, lupin and clover infected by *Cucumber mosaic virus* strain persist between growing seasons in eight alternative host species (McKirdy and Jones, 1994). In USA, the leguminous weed *Desmodium canum* is the alternate host of *Pea mosaic virus* (Demski *et al*., 1981).

4.2. Vectors

Naturally, insect vectors are served as secondary spread for the majority of seed transmitted viruses. The infected seedlings rising from virus-infected seeds used as primary source of infection and more spread by vectors. About 90% of vectors of plant viruses are found in the phylum Arthropoda and 6% are nematodes. Almost 35 seed-transmitted plant viruses are found in Potyvirus group, which have aphid vectors. The next uppermost 28 seed transmitted viruses are in Nepovirus group, in which nematodes are the vectors (Sastry, 2013).

Aphids are the vectors for a sizeable number of seed-transmitted viruses. Their host range, the time of emergence and abundance of winged forms among the population are the significant factors that determine spread of aphid-transmitted virus diseases both in time and space. Aphid species are mostly specific to one or several closely related host plants, while a few are polyphagous and infest hundreds of plant species. Spread of non-persistent viruses is greatly affected by the flight behavior of aphid vectors (Sastry, 2013).

For vector-borne viral diseases, even low rate of seed transmission can be epidemiologically important, because this is the primary source of inoculum that forms the starting point for the initiation of virus disease, ensures the virus association with crops planted in the field and serve as a means for long-distance dissemination. As the infected seeds are randomly dispersed in the field, the seedlings germinating from these seeds serve as sources of inoculum for secondary spread by insect vectors (Sastry, 2013; Regassa et al., 2021).

5. Management of Seed-Transmitted Virus Diseases

Management/Control measures are aimed either at decreasing the virus source or at preventing virus spread within the crop. The different types of control measures available can be classified as: Phytosanitary including removal of infected seed, use of clean seed, rouging, **e**limination of weed, volunteer and crop residues; cultural practices; use of host resistance cultivars, and quarantine.

5.1. Removal of infected seeds

A careful and close look at the seed in certain cases gives an indication of the presence of the virus. Seed morphological abnormalities like shriveled seed coats, discolorations, reduced seed size, cracking, necrotic spots are sometimes associated with the presence of virus in the seed. Small and shriveled seeds of barley, wheat and cowpea indicate the possible infection of *Barley stripe mosaic virus*, *Brome mosaic virus* and *Cowpea mosaic virus*, respectively (Phatak, 1974; Von Wechmar *et al*., 1984). *Soybean mosaic virus* seed infection in soybean can be known by distinguishing seed discoloration and black bands (Phatak, 1974). Routine seed cleaning techniques minimize the extent of infection but can never completely eliminate the viruses. For example, Stevenson and Hagedorn (1970) reduced the transmission of *Pea seed-borne mosaic virus* in a given seed lot from 10 to 4% by removal of infected seeds with growth cracks.

5.2. Chemical seed disinfection

Chemical disinfectants such as sodium hypochlorite, trisodium phosphate and hydrochloric acid for removing viruses carried on the seed coat (Paylan *et al*., 2014). Seed disinfection helps in removing external infection in fruit pulp remnants as in *Tobacco mosaic virus* on tomato, chilli and brinjal seeds and *Cucumber green mottle mosaic virus* on cucumber seeds. *Tobacco mosaic virus* infection in tomato seeds was greatly reduced by treatment of the pulp with one quarter of its volume of concentrated HCl for 30 min, followed by washing and drying of the seeds (McGuire *et al*., 1979). Cordoba-Selles *et al*. (2007) have eradicated the *Pepino mosaic virus* infection from tomato seeds by immersing the infected seeds in 10% trisodium phosphate for 3 h which do not hinder the germination. Svoboda *et al*. (2006) have indicated that capsicum seeds can be disinfected from *Pepper mild mottle virus* by using 2% NaOH.

5.3. Avoiding of continuous cropping

Infection sources, generally from the same crop or from other crops which are susceptible and grown nearby, will lead to severe virus problems (Regassa *et al*., 2021). Some of the crops like tomato, cucurbit, peanut and other legumes are grown throughout the year without any break, and inevitably new crops are grown near old ones. By breaking the disease cycle, it is possible to minimize the spread of virus diseases which have limited host range (Sastry, 2013).

5.4. Elimination of weed, volunteer and wild hosts

Weed and volunteer plants being major components of the agro-ecosystem serve as source of inoculum, since they harbor virus diseases (Thresh, 1981). Even wild plants act as direct source of viruses and vectors. Their removal eliminates the sources of infection, reduces virus spread in seeds if the virus is seed transmitted and also prevents vectors from breeding on them (Sastry, 2013; Regassa *et al*., 2021). Eliminating such sources significantly reduces the rate at which virus epidemics develop within crops.

5.5. Rouging

Rouging is the removal of diseased/symptomatic plants. It is commonly used phytosanitation measure anywhere virus disease control achieved by eliminating diseased plant which serve as initial sources of infection from which further spread can occur. Rouging of virus infected plants can be more effective when the virus disease incidence is very low that could help in minimizing the spread of virus (Sastry, 2013). Regular field monitoring, assessment of virus symptoms and rouging-out diseased plants are helped to prevent further spread of the virus by vectors.

5.6. Crop rotation

Crop rotation aids to avoid infection sources including volunteer crops that may have become infected or have survived from previous crops. It has historically been the most important means of plant virus disease management in production of crops. For example**,** *Tobacco mosaic virus* remains infectious even after 2 years in the old infected root debris and crop rotation is one of the ways of freeing the soil from *Tobacco mosaic virus* satisfactorily, as the root debris and viruses are eventually destroyed by microbial (fungi and bacteria) in cultivated soil. *Tomato mosaic virus* on tomato crop was successfully eliminated by composting tomato residues, and it was due to biological elimination of the virus or due to heat inactivation (Avegelis and Manios, 1989). In USA, crop rotation was effectively used for the management of MCMV (Uyemoto, 1983). Effective monitoring, rigorous implementation of maize-free periods and rotation with non-cereal crops have helped in minimizing maize lethal necrosis (which is caused by co- infection of MCMV and *Sugarcane mosaic virus*) incidence (Mahuku *et al*., 2015; Regassa *et al*., 2022).

5.7. Quarantine

Quarantine is considered as one of the best procedures of controlling movement of seed transmitted viruses (Adams *et al*., 2014). Most countries differentiate between the seed imported for scientific purposes and those imported for sowing or commercial purposes. Since more than 231 viruses are seed transmitted, there is a risk of introducing the virus diseases which are not known to occur in a country if proper testing is not carried out. Even minute quantities of soil and plant debris contaminating true seeds can introduce the virus/vector, or both. Now day's chances of virus introduction are greater with quick and efficient air transport enabling exchange of large quantities of seed material between plant breeders and crop scientists around the world. Thus, man is the direct or indirect cause of most epidemic imbalances and the high virulence and extreme susceptibility of an epidemic situation is an unnatural imbalance usually brought about by human disturbance (Jones, 2000).

5.8. Host plant resistance

Host plant resistance is the major approach to control of viral diseases. It is typically the most economical control measure because it is an economically feasible, environmentally sustainable and requires low input from the producer. Resistance to plant viruses can be due to the inability to establish infection, inhibited or delayed viral multiplication, blockage of movement, resistance to the vector, and viral transmission from it (Jones, 1998). Genotypes that exhibited resistant reaction and restricted the appearance of disease symptoms might carry necessary genes for virus resistance. The defense mechanism plant against viruses could be intermediated by resistance genes which are observed as complete resistance and that the virus replication could be delayed (Ingvardsen *et al*., 2010).

5.9. Integrated cultural practices

A single control method used alone may provide only small, however, it is enhanced through integrated disease management tactics, which combine all possible measures that work in different ways such that complement each other and can be used and applied together in the fields as one overall control package (Jones, 2006; Thresh, 2006).

Summary and Conclusion

Plant viral disease transmitted by seed is a vital means for the introduction of the diseases into new areas where they may become established, spread quickly and can cause epidemics in the presence of appropriate vectors and host species. The seed transmitted viruses could serve as a primary source of inoculum that forms an initial point for the beginning of virus disease, ensures the virus association with crops planted in the field and serve as a means for long-distance dissemination. As the infected seeds are randomly dispersed in the field, the seedlings germinating from these seeds serve as sources of inoculum for secondary spread by insect vectors. The numerous steps of seed transmission that are pertinent epidemiologically are the movement of the virus from mother plant tissues to seed, from the embryo to the progeny seedling, and the role of seed transmission to local and long-distance distribution of viruses caried by seed. The other epidemiological significance of seed transmission is that even at low levels of seed transmission, it can be also transmitted by insect vector, and hereafter can be responsible for the introduction of virus into new local and long-distance geographical areas. Regulatory inspection and restriction through quarantine, regular field monitoring, assessment of virus symptoms and rouging-out diseased maize plants helps to prevent further spread by vectors.

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