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Research Papers

Estimated costs of plum pox virus and management of sharka, the disease it causes

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Summary. The disease "sharka", caused by *Potyvirus plumpoxi* (plum pox virus), is the most harmful viral disease affecting stone fruits. The virus spreads over long distances through illegal and insufficiently controlled exchange of infected propagative plant material. Once established in an area, the virus spreads locally through vegetative propagation of infected plant material, and naturally through aphid-vectors. Previously considered a European problem, sharka has now been reported in 54 *Prunus*-growing countries in all continents except Oceania, although the disease has been eradicated from the United States of America. The economic cost of the disease in the 28 years from 1995 to 2023 is estimated to be €2.4 × 10^9, equivalent to approx. 0.17% of the stone fruit industry's value. This includes more than over €2 × 10^9 in direct fruit losses, €1.4 million from international rejection of symptomatic fruit, and over €100 million in eradication and disease limitation costs. Indirect costs include €137 million, mainly associated with ELISA analyses, and approx. €130 million in costs related to research and science networks. Cumulative global losses from the sharka pandemic since the decade 1910/20 probably surpass €13 × 10^9. These outlays exclude indirect trade costs, economic losses, genetic erosion of traditional cultivars, and the costs of developing new cultivars tolerant or resistant to plum pox virus. The decline in these costs compared to the previously evaluated €10 billion from the 1970s to 2006 is analyzed. Four case studies (for Spain, Turkey, Chile, and Greece) illustrate different sharka scenarios and management strategies.

Keywords. PPV, direct costs, indirect costs, losses, ELISA tests, eradication, subsidies, quarantine, RNQP.

INTRODUCTION

Plant pathogens causing crop diseases are threats to global food security (Strange and Scott, 2005; Savary *et al.*, 2019), and economic losses caused by plant viruses are important (Jones and Naidu, 2019). However, there have been few studies on economic losses caused by viruses in temperate stone-fruit trees (e.g., Paulus and Ullstrup, 1978; Németh, 1994; Tresh *et al.*, 1994; Waterworth and Hadidi, 1998; Matthews and Hull, 2002; Cambra *et al.*, 2006a; Hadidi and Barba, 2011; Rao and Reddy, 2020), while there has been more research evaluating economic losses caused by phytophagous arthropods, fungi (especially those causing foliar damage), or oomycetes (e.g., Culliney, 2014; Simões *et al.*, 2023). Few attempts have been made to establish stone fruit yield, quality, and economic losses caused by the plant viruses.

Diseases can decrease plant productivity and production of marketable fruit. Losses caused by virus diseases depend on many factors, such as prevalence or incidence of infections, severity of diseases, virulence and host range of prevalent strains/variants of virus pathogens, host cultivar susceptibility, duration of infections, and fluctuating prices for crop products. Plant health is closely linked to international trade because invasive pests and pathogens can be introduced through the movement of plants and plant products across borders and continents, disrupting trade and causing economic losses. Direct assessment of the costs of prevention, management, and decrease in crop losses is complex and often imprecise (Oerke *et al.*, 1994; Savary *et al.,* 2019), primarily due to uncertainties surrounding the proportions of non-marketable crop products. This depends on factors such as intended uses of produce, whether for export or local consumption, and the availability of published information and data.

Plum pox ("sharka") is caused by plum pox virus-PPV, and is the most harmful disease of stone fruits. Several authors have reviewed the impacts of this disease on European stone fruit production, especially of apricot and European plum (e.g. Németh (1994), Kegler and Hartmann (1998), Nemchinov *et al.* (1998), Capote *et al.* (2006) and Sochor *et al.* (2012). A broad estimate of the international costs associated with plum pox management, excluding indirect trade losses, has been estimated to exceed €10 × 10^9 (Cambra *et al.*, 2006a) during the 1970s to 2006, since the beginning of the sharka pandemic until the 1970s. Additionally, limited technical resources and a lack of experience in managing the disease led to considerable social and political implications during the early decades of the spread of the disease. The costs associated with the disease involve direct losses in stone fruit production, commercialization, eradication, compensatory measures, and lost revenue, along with indirect costs including those for preventive measures such as quarantine, surveys, inspections, control of nurseries, diagnostics, management measures, and the impacts on foreign and domestic trade (Cambra *et al.*, 2006a; Barba *et al.*, 2011). As well this disease cause losses in national biodiversity and genetic erosion, particularly affecting traditional and well-adapted *Prunus* species cultivated in areas where sharka is endemic, that are very susceptible to PPV.

The plum pox virus and sharka disease: an overview

Plum pox virus (*Potyviridae*, *Potyvirus plumpoxi*), the causal agent of sharka, is to date the only potyvirus known to infect temperate fruit trees. PPV is a well-characterized virus (Sochor *et al.*, 2012; García *et al.*, 2014; Rimbaud *et al.*, 2015; García *et al.*, 2024), and is considered one of the top ten viral pathogens (Scholthof *et al.*, 2011) of high scientific and biotechnological relevance. PPV diversity is currently structured into ten monophyletic strains, that in the chronological order of discovery, are: Dideron (D), Marcus (M), El Amar (EA), Cherry (C), Recombinant (Rec), Türkiye (T), Winona (W), Ancestor M (An), Cherry Russian (CR), and Cherry Volga (CV) (EPPO, 2023). The different strains have specific genome sequences, and may vary in their spectra of natural hosts, symptomatology, pathogenicity, epidemiology, aphid transmissibility, and geographical distributions with some restricted to particular regions. Some degree of within-strain variation has also been observed.

Three predominant strains have broad geographical distributions. These are PPV-D, PPV-M, and PPV-Rec (García *et al.*, 2014). PPV-D is widespread in Europe, and is the cause of most PPV outbreaks in North and South America and Asia. This virus is found in all *Prunus* species except cherry. PPV-M has been reported mainly in Central and Southern Europe and Japan, and affects all *Prunus* species except cherry and causes rapid epidemics in different peach cultivars. PPV-M generally causes more severe symptoms than PPV-D. PPV-Rec has a similar epidemiology to PPV-D, but is less adapted to peach, and has been reported mainly in several European countries. PPV-EA has only been reported in Egypt, in several *Prunus* species except cherry and almond. PPV-C is widespread in Russia, common in Moldova, and has occasionally been reported in Belarus, Croatia, Hungary, Germany and Italy restricted to sour (*P. cerasus*) and sweet (*P. avium*) cherries. PPV-T is common in Türkiye, found in several *Prunus* species except for cherry and almond. PPV-W has been reported in Eastern European countries and Canada, in several *Prunus* species except for cherry and almond. PPV-An is found in Eastern Albania in several *Prunus* species except for cherry and almond. PPV-CR and PPV-CV are cherry adapted strains that were discovered in Russia on sour cherry (Glasa *et al*., 2013; Jelkmann *et al*., 2018; Oishi *et al*., 2018; EPPO, 2023; García *et al*., 2024).

The geographic distribution of PPV is increasing. Since sharka was first reported in Bulgaria in 1917-1918 on *Prunus domestica* by Atanasoff (1932), and in 1993 in apricot trees (Németh, 1994), the virus is now officially present in most of continental Europe, with endemic status in many central and Southern European countries. The virus has progressively spread to many countries (currently 54) in nearly all continents. Reported incidence of emerging and re-emerging PPV is increasing in new areas where *Prunus* stone fruit industries are important (García *et al*., 2024). Mexico is the most recent country of reported PPV (Loera-Muro *et al*., 2017). As the virus is efficiently transmitted through grafting and other vegetative propagation methods, the primary pathway for PPV spread over long distances is illegal trafficking and insufficiently controlled exchange of infected, symptomless, propagative plant materials (Cambra *et al*., 2006a; EPPO, 2024). Once PPV has become established in an orchard, vector aphids naturally spread the virus locally, through a nonpersistent stylet-borne inoculum mechanism.

PPV is the only stone fruit virus transmitted by aphids over short distances within and between orchards. The feasibility of experimental PPV transmission from infected fruit has also been reported (Labonne and Quiot, 2001; Gildow *et al*., 2004), but PPV is a non-persistent virus, which is acquired by insect vectors and inoculated during short periods, without any latent period. This putative transmission method has had economic repercussions, evidenced by batches of infected fruits from Chile being rejected in Brazil due to virus detection (Rezende *et al*., 2016). Madariaga *et al.* (2024) compared relative accumulation of PPV load between freshly harvested infected fruit and fruit subjected to cold storage, simulating transit conditions to export markets over two consecutive seasons. Their study showed reduction in viral RNA in fruit exposed to cold storage compared to freshly harvested fruit. The known aphid species colonizing or visiting *Prunus* spp. and described as PPV-vectors include 29 species (Labonne *et al.* 1995; Kimura *et al*., 2016; Cambra and Vidal, 2017).

A statistical model for PPV prediction in *Prunus* nursery blocks using vector and virus incidence data is available (Vidal *et al*., 2020). Sharka epidemiology and PPV dissemination have been addressed by Gottwald *et al.* (2013), Rimbaud *et al.* (2015), and Gutiérrez-Jara *et al.* (2023). The woody host list (EPPO-Global Database, 2020; Chirkov *et al*., 2022) includes cultivated, wild, and ornamental *Prunus* species and hybrids, among them *Prunus fruticose,* the latest species described as a PPV host, as well of non-rosaceous woody plants such as *Spiraea* sp. and *Tilia* spp. (García et al. 2024).

PPV infections cause the most detrimental diseases of stone fruit trees, as these can severely reduce fruit quality and induce premature fruit drop in some cultivars, especially in *P. domestica* (Figure 1, a and b). Symptoms of sharka may appear on host leaves, shoots, bark, petals, fruit, and fruit stones (Damsteegt, 2008; García *et al*., 2014; Rodoni *et al*., 2020). Because PPV is easily transmitted by aphids and by vegetative multiplication, production of PPV-free plants is difficult. Specific

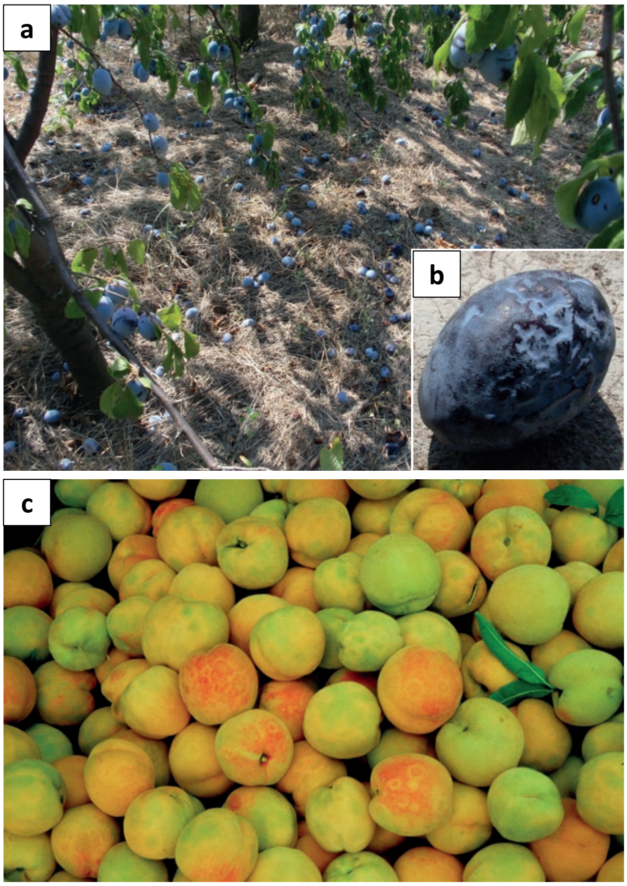

Figure 1. Typical symptoms induced by plum pox virus (PPV): (a) on a highly susceptible plum cultivar showing premature fruit drop; (b), symptoms on a fruit from the same cultivar; (c) 'Catherine' peach fruit discarded in a packinghouse, showing sharka symptoms. Photograph credits: a and b, Dr M. Glasa; c, Dr M.A. Cambra, (Centro de Protección Vegetal y Certificación, DGA, Montañana-Zaragoza, Spain. Photograph c is part of the photograph gallery accessible to members of GEDDI-Spanish Society of Phytopathology (SEF).

regulatory and control strategies need to be implemented to curb the disease in nurseries, requiring considerable effort by nurserymen and frequent inspections. Foliar treatments with horticultural mineral oil as a physical barrier have been shown to reduce natural PPV infections in nursery blocks (Vidal *et al.*, 2010). The disease does not kill infected trees; but if they are not removed from orchards, they become reservoirs of PPV (Cambra *et al.*, 2006a; EPPO PRA, 2012).

The presence of PPV in a country creates difficulties for export of certified planting material and for fruit. Visual inspections cannot guarantee the sanitary status of individual plants, so the use of analytical methods may be necessary for accurate diagnoses (Rimbaud *et al.*, 2015). A range of diagnostic tools are used for detecting PPV. Diagnosis is currently based on integrated approaches, which include biological indexing and serological and molecular amplification assays (EPPO, 2024). Despite the development of many sensitive nucleic-acid-based techniques, the ELISA technique remains the most common for PPV detection (Cambra *et al.*, 2011; Rimbaud *et al.*, 2015). Several PPV detection kits are available, based on specific monoclonal or polyclonal antibodies, and the ELISA method is appropriate for large-scale testing and has low per sample cost.

Serological tests have been, and continue to be, key for PPV management (detection and diagnosis), despite the poor assessment of these methods provided by the most recent EPPO (2023) standard for PPV diagnosis, compared to previous EPPO standards and IPPC-FAO (2018). This is likely due to the lack of experience in serological methods of teams that carry out the EPPO validations. Currently, the technique of choice for nucleic acid-based PPV detection is reverse transcription quantitative real-time PCR (RT-qPCR), with loop-mediated isothermal amplification (LAMP) being another option. Protocols are available for direct use of plant crude extracts or immobilized tissue-prints of plant or squashed vector samples feasible as PCR targets, instead of purified RNA (Capote *et al.*, 2009). This opens the possibility of large-scale use RT-qPCR. Biological, serological and molecular amplification methods for PPV detection and identification have been summarized by Rimbaud *et al.* (2015) and IPPC-FAO (2018), and a number of novel molecular amplification methods are referenced in EPPO (2023).

Research and innovation in plant breeding (including search for cultivars resistant or tolerant to PPV, and pathogen-derived resistance in transgenic *Prunus* species), pest control, and orchard management all contribute to the continued advancement of stone fruit production, which is threatened by PPV. The economic costs of these innovations, representing an indirect cost associated with sharka, has been partially assessed as research in the present paper. An example is the PPV-resistant, genetically engineered *P. domestica* cultivar HoneySweet (Ravelonandro *et al.*, 2013; Scorza *et al.*, 2016), which was deregulated in 2007 in United States of America (USA) (Scorza *et al.*, 2007).

Recognition of plum pox virus as a pest by plant protection organizations

PPV was included in the EPPO A2 list (version 2023-09) of quarantine pests recommended for regulation in the EPPO countries since 2000. However, according to European Union (EU) legislation in 2019, the virus was reclassified as a regulated non-quarantine pest (RNQP), defined as ‘a non-quarantine pest whose presence in plants for planting affects the intended use of those plants with an economically unacceptable impact and which is therefore regulated within the EU territory′ (EU regulation 2016/2031). This transcendental decision was primarily made due to PPV being already present and widespread across most EU countries, with difficulty or impossibility of PPV eradication from several areas (Pedrelli *et al.*, 2024). Therefore, pest infestation may be tolerated (as plants for planting which infected above a given threshold would result in unacceptable economic impact). Consequently, farmers are compelled to directly manage PPV in EU countries, although private management of diseases such as sharka is generally inefficient (Martinez *et al.*, 2024). The concept of RNQP has been implemented in the EU Plant Health Law (EU Regulation 2016/2031), specifically for professional operators. Currently, PPV is also of regulatory interest to other Regional Plant Protection Organizations which recommend their member countries to regulate PPV as a quarantine pest locally present in their region (A2 list). These organizations include: i) APPPC-Asia and Pacific Plant Protection Commission, which includes 25 member countries; ii) the COSAVE-Comité de Sanidad Vegetal of Cono Sur, including Argentina, Bolivia, Brazil, Chile, Paraguay, Peru, and Uruguay; iii), the -North American Plant Protection Organization (NAPPO); and iv) the -Inter-African Phytosanitary Council (IAPSC), which declares PPV as absent (list A1) in African countries except Egypt, Morocco, and Tunisia. In these organizations, except for the EU, quarantine measures (exclusion, eradication, containment) aim to prevent unacceptable economic, environmental, and social impacts resulting from the introduction and spread of named pests (in this case PPV). These measures are mandatory and imply direct and indirect disease management-associated costs. Furthermore, some countries have regulated or prohibited the importation of PPV-susceptible planting material from countries where PPV is declared, or which have adopted strict regulations regarding the conditions of plant production in the exporting countries (Rimbaud *et al.*, 2015). NAPPO and COSAVE member countries implement phytosanitary controls at entry, or indexing of imported plant material confined in post-entry quarantine facilities (e.g., NAPPO, 2009). Similarly, this system was implemented in countries free of PPV, such as Australia (Rodoni *et al.*, 2006) and New Zealand (Lebas *et al.*, 2006). This strategy and its legal framework entail significant costs associated with preventing the entry of PPV, which are not evaluated in the present study.

Relevance of stone fruit industries in countries where PPV has been detected

Prunus stone fruit trees (excluding almond) are important in food production. In 2019, stone fruit production totaled approx. 49 million t, and was cultivated across approx. 5 million ha (FAOSTAT, 2023). The average estimated value of stone fruit production for 1995 to 2023 is approx. €51 × 10^9 per year. This estimate is based on generalized assumptions about production volumes, market prices, and growth rates over time, according to FAOSTAT data. This value includes production of: common and Japanese apricots, peaches (clingstone, freestone, semi-freestone, yellow fleshed, white fleshed, donut or flat, nectarines, blood peaches), European, Japanese, and green plums (*Prunus cerasifera*), and sour and sweet cherries. Additionally, almonds (production of 3.2 million t in 2019) are cultivated across numerous countries where sharka is spreading. The significant economic value of stone fruit trees includes direct revenue generated from fruit sales as well as income generated along supply chains, including farming, processing, distribution, and retail. These fruit products also offer nutritional benefits and are part of different cultural traditions.

PPV has been detected in the main stone fruit-producing countries, except in Australia, New Zealand and the Republic of South Africa. China is the greatest producer of stone fruits (Huang *et al.*, 2008; Guillesky, 2018), and PPV infections have potential to cause major economic damage to the stone-fruit industry in that country (Xing *et al.*, 2017). Nevertheless, despite the presence of sharka, countries such as Italy, Spain, and the USA remain prominent producers of stone fruit and almonds, making substantial contributions to global production (FAOSTAT, 2023). Chile (Retamales, 2011) and Argentina have also emerged as key players in the Southern hemisphere, exporting substantial volumes of stone fruit to international markets during their respective growing seasons. Türkiye is an important country for apricot, cherry, peach and plum production (Bolat *et al.*, 2017; TURKSTAT 2023), and significant are Iran (Ghahremani *et al.* 2023) and Greece (Huang *et al.*, 2008; OPEKEPE, 2023) as peach producers.

Overall, the period from 1995 to 2023 has seen important increase in world cultivation and production of stone fruit varieties, which has been driven by technological, economic, and environmental factors. The stone fruit industry generates significant value and provides income for growers, processors, distributors, exporters, and retailers.

MATERIAL AND METHODS

Direct losses and cost estimation

The estimated direct costs associated with sharka management primarily include those related to production losses: premature fruit drop and rejection of symptomatic fruit in packinghouses, usually expressed as percentages. Losses due to the rejection of symptomatic fruit batches during export have been assessed only in sporadic reported cases. Estimated costs due to the eradication of productive field trees or plant blocks in nurseries have also been evaluated, although direct losses from unmarketable planting material if PPV is detected are not included due to the lack of available data. The value of subsidies, or compensation and loss of income costs, based on official data from countries actively managing sharka, have been included when available.

Production of each species is primarily estimated using agricultural production data available from FAOSTAT (2023), and adjusted to estimate costs in Spain with data from the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 2021) and official information from local Plant Protection Services. Production information was retrieved mainly for the top ten producer countries of each crop, and the production averages were calculated for the period 1995–2023, during which a significant increase in cultivation occurred. Production was also adjusted in some cases with more local statistical data, including ISTAT (2023) for Italy, TURKSTAT (2023) for Türkiye, and OPEKEPE (2023) for Greece. Direct losses were calculated based on the estimated percentage of unmarketable fruit for specific crops. The estimates were based on information about PPV strains present in each country and the reported extent of the disease (Damsteegt, 2008; Loera-Muro *et al.*, 2017; Zhou *et al.*, 2021; EPPO, 2024; Pedrelli *et al.*, 2024). To estimate percentage losses, typical losses were estimated for each stone fruit species, along with information obtained from packinghouses, local experts, and evaluations by the present study authors. Despite the considerable variability from year to year, the estimated losses were considered fixed across all seasons and for each year during the evaluated period, for fresh, dried, or canned fruits. However, cool springs tend to generate more disease symptoms, due to the coinciding development of fruit with increased viral titer compared to warmer springs. Sometimes, in early cultivars, fruit is more affected than for later cultivars. However, this was not considered in the present study, due to the complexity of determining which years were more favorable for symptom expression in each production area. In Spain, monetary value was mainly calculated based on the average prices for fresh fruit during 2010 to 2020, according to data provided by MAPA (2021). These values were (for 100 kg bulk pallets): for peaches, 1.3 € kg^{-1}); for plums, 0.90 € kg^{-1}; and for apricots, 0.59 € kg^{-1}. The reference prices, based on export values of quality fresh stone fruit, reflects Spain's position as a major exporter (EC, 2022). For estimating global losses (excluding Spain), retail prices perceived by farmers in local markets were used, as well as prices for bulk exported fruit. These values ranged from a minimum to a reference price ex-packaging station (EU, 2023) for: peaches, 0.4–1.3 € kg^{-1}; plums, 0.25–1.0 € kg^{-1}; apricots, 0.15–1.3 € kg^{-1}; and cherries, 0.2–1.7 € kg^{-1}. To calculate the value of losses, the lowest value was used, even if it fell below the estimated production cost price of peaches for Spanish farmers, which is approx. 0.4 € kg^{-1} (CREDA, 2023). The retail price used for fresh apricots from some areas (including Beijing, China) was 0.5 € kg^{-1}. A comprehensive overview of current prices, markets, and trade is available in various publications (e.g., Mulderij, 2018).

Direct economic losses due to rejection of fruit with sharka symptoms were evaluated according to the documented case of Chile Brazil border in the 2016–2017 season, which is the only reported international case. However, sporadic reports fruit showing sharka symptoms in supermarkets have appeared in local newspapers and online commercial documents reports, but these have not led to significant consequences. The economic feasibility of eradication or disease removal efforts was evaluated based on data from the literature.

The losses of biodiversity and genetic heritage due to sharka, primarily affecting traditional European plum and apricot cultivars, is mentioned but has not been evaluated. This situation occurs particularly in European countries where the sharka is endemic, and resilience is achieved through the use of tolerant cultivars.

Estimations of indirect losses.

Indirect costs include those for disease preventive measures, including pre- and post-quarantine facilities, surveys (at a reference cost of €35 ha^{-1}), inspections, prevention measures, special facilities in nurseries, nursery control, and selection in packing houses to remove symptomatic fruit. Additionally, sampling and diagnostics, development of specific laws, policies for compensation to affected growers, research and development investments, and the impacts on foreign and domestic trade should be estimated. Among indirect costs, those with available data for calculation have been evaluated. The most readily available are costs associated with disease detection and diagnosis, and for research grants. Costs for surveys and inspections have been partially estimated for some countries.

ELISA serological tests are important for management of PPV. Numbers of ELISA tests performed annually were estimated, by consulting the main international companies that market PPV kits for screening, universal detection, or for identifying PPV isolates (mainly PPV-D, PPV-M and PPV-C). The international companies that collaborated by providing data were: AMR Lab, Spain, currently integrated into Plant Print Diagnostics; Agdia, USA (https://www.agdia.com); Agritest, Italy (https://agritest.it); Bioreba, Switzerland (https://www.bioreba.ch/bioreba.aspx/t_new); Plant Print Diagnostics, Spain, (including former AMR Lab and Real-Durviz kits, https://plantprint.net); and Prime Diagnostics, The Netherlands (https://primediagnostics.com).

The pandemic condition of sharka and the perceived importance of the associated socio-economic losses have led to research focused on basic molecular aspects of PPV and its potential as a biotechnological tool (García *et al.,* 2014; García *et al.* 2024). These studies began in Europe and have expanded to other regions where PPV was detected. In parallel, programmes were initiated aiming to introduce resistance to PPV into elite cultivars of apricot, European plum, and peach, and to develop strategies to reduce virus spread and virulence, such as transgenic protection, immunomodulation, RNA silencing, and Spray-Induced Gene Silencing (SIGS) (Cirili *et al.*, 2016; De Mori *et al.*, 2020; García *et al.*, 2024). This research activity has required significant financial investment, which is challenging to quantify, as it has been accompanied by numerous field trials, such as the genetically engineered plum cultivar HoneySweet (Scorza *et al.*, 2016). The amounts invested in research have been obtained from data available from the main funding agencies for research projects in the countries that are most active in this field.

RESULTS AND DISCUSSION

Direct losses and cost evaluation

The general data are summarized in Table 1. Direct economic losses due to the rejection of fruit with symptoms at country borders have likely occurred in several countries, but the most recent documented cases, related to Chile, have occurred at the Brazilian border. Rejections occurred in the 2016-2017 season, for 525,440 t of nectarines (31.2% of the rejected fruit), and plums (68.8% of the rejected fruits), with associated cost of €1.4 million (Chilean customs). These costs included export expenses, the value of product, and legal and regulatory fees. However, some costs were not accounted for, including reputation damage, opportunity costs if the rejected shipments were part of larger sales plans, lost potential revenue and market expansion opportunities due to the inability to sell fruit to Brazilian markets, and remediation costs if corrective actions were required to meet Brazilian import regulations. However, after multiple negotiations, it was accepted that stone fruit infected by PPV-D did not pose risks of spreading the virus, and PPV is no longer regulated in Chilean exports.

Eradication or disease removal was a goal during the early years of the sharka epidemic, but this was technically challenging due to the lack of serological methods and large-scale kits with high specificity antibodies for testing large numbers of plants (Cambra *et al.*, 2011). Currently, eradication of PPV is feasible if there is commitment to protecting the stone fruit industry, along with political will, support from farmers, appropriate subsidies, and supportive laws. The cost-benefit ratio of eradication is favourable. The direct costs of eradication can be evaluated for some countries that have attempted this with total success (USA), partial success (Canada), or failure after years of attempts (Spain). In countries where initial outbreaks of PPV were discovered with low prevalence in geographically restricted areas, eradication programmes could be undertaken without compromising the stone fruit industries. Canada and USA are good examples of how stringent procedures lead to successful reduction of inoculum (in Canada), at least in some

Table 1. Estimated world direct (A) and indirect (B) economic costs [million euros (€)] associated with management of plum pox virus and sharka in Prunus fruit crops during the period 1995 to 2023.

A. Direct costs					
	Virus strain	Region/Country	Cost (million €)[a]		
			Partial	Subtotal	Total
Prunus fruit types					
Apricot	PPV-D[b]		389.76		
	PPV-M[c]		175.64		
				565.40	
Plum		Europe	910		
		China	37.52		
		Third group[d]	1.11		
		Fourth group[e]	0.12		
				948.75	
Peach			*511.56*	*511.56*	
Cherry			*na*[f]	*na*	
					2,025.71
Border rejections		Brazil/Chile	1.4	***1.4***	
Eradication and disease removal		USA	30.3		
		Canada	50		
		Spain	13.5		
		Other countries[g]	6.2		
				100	
					2,127.11

(Continued)

Table 1. (Continued).

B. Indirect costs

	Test type	Region/Country	Cost (million €)[a]		
			Partial	Subtotal	Total
Pathogen detection and diagnoses	Serological tests		120		
	Molecular amplification tests and sequencing		17		
				137	
Research		EU	27.7		
		Russia	0.36		
		Chile	0.94		
		USA	90		
		Other	11		
				130	
					267
TOTAL (A+B)					**2,394.11**

[a] Estimated million euro amounts are expressed in nominal values (without adjustment for inflation). When data were available in US dollars, the conversion to euros was made using the 2023 exchange rate.

[b] Estimated for Argentina, China, Cyprus, Canada, Croatia, Egypt, France, Germany, India, Iran, Israel, Italy, Japan, Jordan, Kazakhstan, Mexico, Pakistan, Portugal, Russia, Spain, Syria, Türkiye, Tunisia, Uzbekistan, and Ukraine.

[c] Estimated for Albania, Bulgaria, Bosnia and Herzegovina, Greece, Moldova, North Macedonia, Poland, Romania, Serbia, Slovakia, and Slovenia.

[d] Estimated for Chile, India, Iran, Serbia, Russia, Türkiye, Ukraine, and Uzbekistan.

[e] Estimated for Argentina, Armenia, Bosnia and Herzegovina, Israel, Kazakhstan, Mexico, Moldova, North Macedonia, Syria, and Turkmenistan.

[f] na, not analyzed.

[g] Estimated for Argentina, China, Chile, France, Italy, Japan, Lithuania, Portugal, the Netherlands, and Türkiye.

states, or eradication of the pathogen (in the USA) (Rimbaud *et al.*, 2015).

In the USA, PPV was first detected in Pennsylvania in 1999 (Levy *et al.* 2000), and later in Michigan and New York State in 2006 (Snover-Clift *et al.*, 2007). To prevent further spread of sharka, which threatened the country's stone fruit industry, valued at approximately €5,355 million (US$ 6.3 billion), the USDA quickly issued an emergency declaration providing much-needed funding and support for eradication of PPV across the country. Within 10 years, PPV eradication was achieved in Pennsylvania (Welliver *et al.*, 2014) and later in other areas of USA (USDA, 2019). This was confirmed by the NAPPO, after three consecutive years of stone fruit field surveys with no further PPV detections. Costs associated with eradication in the USA amounted to approx. €30.3 million (Welliver *et al.*, 2014), which included analysis of 1.9 million samples using ELISA, removal and destruction of 750 ha of stone fruit plants (approx. 188,000 trees), and compensation for lost fruit production, among other expenses.

In Canada, PPV was detected in Ontario and Nova Scotia in 2000 (Thompson *et al.*, 2001). An eradication programme was then initiated, with intensive surveys that led to the removal of 264,000 trees in 6 years, following analyses of over 2.6 million samples using ELISA (Thompson, 2006). Despite a total expenditure of approx. €50 million until 2010 (including the analyses of 3 million trees using ELISA, and indemnities), the programme was terminated in 2011 without fully eradicating the pathogen. However, the programme achieved a significant reduction in inoculum and other disease management benefits (Gottwald *et al.*, 2013).

In the important stone fruit industry of Spain, detection of PPV-D in 1984 raised significant concerns due to potentially severe damage, mainly in apricot trees, which suffered losses estimated at 5% by 1998. This prompted a voluntary eradication programme, resulting in the uprooting of more than 2.3 million trees from 1989 to 1998, at a total cost of over €63 million, including tree removal and indemnities (Cambra *et al.*, 2006b). During the period 1995 to 2023, approx. €3 million was spent on subsidies for uprooting PPV-D infected trees. PPV-M was first detected in Spain in 2002 in the Autonomous Community of Aragón near the border with Catalonia, and the pathogen was subsequently eradicated (Capote *et al.*, 2010). Over the next 8 years, there were no further detections of PPV-M in commercial stone fruit orchards in the area, suggesting successful eradication. However, in 2016, several new foci of PPV-M were again detected in Catalonia and neighboring Aragón in the northeast of the Iberian Peninsula. The costs associated with a renewed tree removal programme were about €10.5 million, including analysis of approx. 1 million samples using ELISA.

The direct costs associated with eradication efforts in the USA, Canada, and Spain totaled €93.8 million from 1995 to 2023. This total should be supplemented with costs incurred in other countries, particularly in Northwestern Europe, where local eradication programmes have been implemented or are ongoing, such as Switzerland, Denmark and Sweden, despite their respectively low stone fruit production (Capote *et al.*, 2006; Rimbaud *et al.*, 2015). Additionally, expenditure on efforts to reduce inoculum or limit disease spread, mainly in Argentina, China, Chile, France, Italy, Japan, Lithuania, Portugal, the Netherlands, and Türkiye, evaluated at €6.2 million, should be included in the total costs. As an example, in Türkiye, approx. €60,000 were paid to producers for tree removal during 2019-2023. Given the difficulties with international cost evaluation, an estimate of the direct costs associated with eradication and disease control in all areas where susceptible fruit trees are grown likely surpassed €100 million from 1995 to 2023.

Evaluation of indirect costs

General data are summarized in Table 1. According to information received from the leading diagnostic companies that market kits based on PPV-specific monoclonal (MAb) or polyclonal (PAb) antibodies, approx. 20.5 million serological analyses were performed using ELISA between 1995 and 2023. Of these, 5 million tests were conducted using the CP broad spectrum PPV-specific monoclonal antibody 5B/IVIA-PPD (MAb) (Candresse *et al.*, 2011), and more than 15 million tests were conducted with PAbs or a cocktail of MAb-PAbs. Additionally, other companies or research institutes have probably marketed or conducted approx. 4 million tests, particularly in Europe, China (Guo *et al.*, 2023) and Japan (Oishi *et al.*, 2018). During the period in which various eradication programmes were implemented in Canada, the USA, and Spain, the total number of ELISA tests performed would reach approx. 24 million. This averages to more than 857,000 tests done annually. The costs of these serological tests, including sample collection, are estimated at approx. €120 million. In addition, expenses associated with molecular amplification techniques (each test estimated at €15, including sample collection), and high-throughput sequencing technologies (each test current cost of €550, including bioinformatic analysis) should also be included. For example, in Russia, where molecular amplification techniques have been widely used since 2010, approx. 10,000 RT-PCR assays have been conducted to confirm PPV infections, determine the PPV strains, sequence the 3'-terminal (Cter-NIb-CP-3'-UTR) genome regions, and validate HTS results. Approx. 50 full-length PPV genomes were determined using a high-throughput sequencing approach, and 3,000 PCR products were sequenced bidirectionally by the Sanger method using the facilities at Evrogen (Moscow, Russia). The total Russian expenses are estimated to be €240,000, excluding ELISA (approx. 2,500 tests performed). It is estimated that the total world annual cost of molecular amplification and sequencing probably exceeded €600,000 during the analyzed period, totalling approx. €17 million. This brings the total world costs for detection, diagnoses, and characterization of PPV to greater than €137 million (Table 1).

Costs linked to investments in research projects and development of PPV-resistant plants have primarily been applied in Europe, with subsequent efforts extending to other countries as PPV detection increased. Among European projects, notable initiatives funded by the European Union (EU) during the period 1995-2023 include SharCo (2008–2012), "Containment of sharka virus in view of EU-expansion, FP7-KBBE-Specific Programme 'Cooperation': Food, Agriculture and Biotechnology (https://cordis.europa.eu/project/id/204429/reporting/fr), and the EU project MARS (2013–2015), "Marker Assisted Resistance to Sharka", which focused on the production of sharka-resistant stone fruit cultivars (https://cordis.europa.eu/project/id/613654). These projects have received approx. €5.4 million, along with other smaller research projects and networks (€3.3 million), totaling approx. €8.7 million. In addition to these, there have been national and bilateral funding initiatives, primarily in France, Italy, Poland, Romania, and Spain (approx. €15 million), as well as contributions from other EU member countries (approx. €4 million). In total, these efforts in the EU have amounted to approx. €27.7 million (from 1995 to 2023).

In Russia, PPV investigations were financially supported by the Russian Foundation for Basic Research (RFBR), the Russian Science Foundation (RSF), and the Ministry of Science and Higher Education of the Russian Federation. Since 2010, the total amount of all grants has been approx. €360,000.

The Government of Chile, through institutions such as National Research and Development Agency (ANID), the

Agricultural and Livestock Service (SAG), and the Agrarian Innovation Foundation (FIA), has allocated funds totalling €940,000 primarily for epidemiological studies.

Funds invested in research projects in the USA through the United States Department of Agriculture (USDA), the Agricultural Research Service (ARS), the National Institute of Food and Agriculture (NIFA), and the Animal and Plant Health Inspection Service (APHIS), from the time of the initial sharka outbreak and response (1999 to 2003), through ongoing disease management and research (2004 to 2019), to the final eradication declaration in 2019, are estimated at approx. €90 million. This includes some specific funding and support for eradication of PPV across the country and bilateral actions with other countries.

Funds invested by other leading stone fruit producer countries for PPV research and management are difficult to quantify, owing to lack of specific and detailed public financial records. Argentina, Brazil, India, Japan, and other countries, are also investing in PPV research, estimated at about €11 million. Consequently, estimated total funds devoted to this research likely exceeded €130 million from 1995 to 2023 (Table 1).

An indirect indicator of the costs associated with scientific and technical research is the number of resulting articles and patents published by the end of June 2024, which totalled 16,200 (retrieved from Google Scholar using the keywords 'sharka disease,' 'plum pox virus,' and 'Plum pox potyvirus').

Case study for Spain

According to FAO (2024) and Batlle *et al.* (2018), Spain is a leading stone fruit producer, with production having significant socioeconomic impacts. Sharka was detected in Spain in 1984, and the direct losses due to fruit rejection of Prunus stone fruit are here assessed.

Peaches and nectarines (*Prunus persica*) are the primary stone fruit grown in Spain, with the country ranking as the second or third largest producer, after China and alternating with Italy. Peach cultivation in Spain accounts for 54.2% (about 80,000 ha) of the prunus industry´s total surface area, generating an average national production of approx. 870,720 t of fruit, and with a clear trend for increased cultivated surface area and production, reaching about 2.5 million t in 2016/17. Non-marketable peach fruit due to sharka symptoms are currently estimated at 0.5% of the total produced. This results in annual estimated losses of approx. 4,354 t year^{-1}. Over the evaluated 28 year (1995 to 2023), this total loss of fruit is valued at approx. €158,500 at the average price of €1.30 kg^{-1}. Losses of fresh peaches are relatively low (Samara *et al.*, 2017), because differences in production or harmful effects were not observed when comparing healthy and PPV-D infected trees in Canada, except for symptoms in fresh fruits that rendered them unmarketable (Figure 1c). Nevertheless, most of the fruit could be used for canned product, even though they presented symptoms. The crop is scarcely affected by the predominant PPV-D isolates endemic in some regions (mainly in early-season producing areas of nectarines along the Mediterranean coast). PPV-M was detected in 2016, however, in medium and late-season peach-producing areas, where the main estimated losses have been associated with preventive eradication campaigns.

For plum trees, early cultivars of Japanese plum (*P. salicina*) are the most cultivated, whereas European plums (*P. domestica*) are of little importance. Together, these plum species represent 5.8% (about 16,000 ha) of the Spanish stone fruit growing area, with average annual production of 222,020 t during 1995 to 2023. Rejection rates are estimated at 1.0% of annual harvests, resulting in annual estimated losses of €1,110,100 (based on €0.5 kg^{-1} in 100 kg pallets). Over the evaluated period, this accounts for more than €31 million in losses. However, this is probably an under-estimate because the selling price in 2021-2022 was €0.90 kg^{-1}.

Apricot tree cultivation was for 4.4% (approx. 20,000 ha) of the Spanish stone fruit growing area during 1995 to 2023, with average annual production estimated at 154,000 t. The crop was severely impacted by the prevalent PPV-D strain from 1984 to 1995, particularly in early cultivars grown along the Mediterranean coast (Martínez-Gómez *et al.* 2000). This lead to an estimated 5% of unmarketable fruits. However, inoculum reduction was achieved through a voluntary eradication programme which removed 2.3 million trees, mainly apricot, as well as use of certified virus-free planting material and adoption of PPV-tolerant cultivars. This led to decreased proportions of unmarketable fruit to approx. 1–2% of the annual harvests from 1995 to 2023. These improvements helped Spain maintain its position as the leading international exporter of high-quality fresh apricots. With an average price at origin of €0.59 kg^{-1} (2010-2020), the losses are estimated at approx. €1.81 million year^{-1}, totalling more than €50.6 million for 1995 to 2023.

Currently, no fruit losses are associated with sharka for cherries and almonds in Spain, where PPV-D is the prevalent strain, and PPV-M outbreaks are under eradication from eastern Spain. Consequently, the total estimated direct harvest losses due to sharka amount to approx. €81.76 million for 1995 to 2023. The value of direct compensation for tree eradication (i.e., subsidies and compensations) relating to outbreaks of PPV-D and

PPV-M was €17.75 million, bringing the total value of direct losses to more than €99.51 million.

The total indirect costs associated with surveys, sampling, and laboratory analyses are calculated at €6.37 million during 1995 to 2023. Approx. 35,000 samples were analyzed annually, primarily using ELISA tests based on universal and strain-specific monoclonal antibodies, at a cost of €5 per test, including field sample collection. This leads to an estimated cost of more than €5 million, which includes costs for several identification procedures based on molecular amplification and sequencing techniques. The extent of surveys conducted in Prunus nurseries and in the field, especially for PPV-M prevention, is estimated at 39,500 ha year^{-1}, with an estimated cost of €35 ha^{-1}, totalling €1.38 million during 1995 to 2023.

In summary, the total direct costs (€99.51 million) and the primary indirect costs (€6.38 million) associated with sharka management in Spain, excluding indirect trade losses, amount to approx. €105.89 million for the period 1995 to 2023. This represents an average of €3.782 million per year, which is about 0.32 % of the average annual value of the production of apricots, peaches, and plums in Spain (estimated at approx. €1,174 million). This estimate was made for the current epidemiological situation: PPV-D is prevalent in some areas, whereas PPV-M remains in isolated pockets under eradication programmes in the Northeast Iberian Peninsula.

Case study for Türkiye, at the Europe Asia boundary

Türkiye is a major world stone fruit-producing country (FAO, 2024). For apricots, Türkiye is a leading producer, and exports substantial amounts of apricots as fresh or, particularly, dried product, playing an important role in the country's agricultural sector and in international trade. Although the first report of sharka was in 1968, the disease was confined to germplasm collection orchards and home gardens. Sharka did not spread to commercial orchards until the early 2000s (Çağlayan and Gazel, 1998; Çağlayan and Yurdakul, 2017). When severe PPV symptoms were observed in commercial stone fruit orchards in 2004, the Ministry of Agriculture and Forestry organized extensive surveys in 56 of the 81 provinces of Türkiye. A total of 5,762 samples were collected from almond, apricot, mahaleb, cherry, nectarine, plum, peach, sweet and sour cherry orchards, and were tested for PPV by biological indexing, ELISA, and RT-PCR. Among these samples, 222 plants were found to be infected with PPV (Akbaş *et al.*, 2011).

Greater incidence and impact of sharka has occurred since 2013. Therefore, assessment of damage and costs associated with the disease have been evaluated over the past 10 years, by crops according to TURKSTAT (2023) and for some local sources. Peach cultivation in Türkiye ranks fourth in production area after apricots, cherries, and almonds, and ranks third in world production (1,008,185 t) (FAOSTAT, 2023). For 2023 production, the average proportion of peach fruit that could not be marketed due to PPV is estimated at 0.05%, resulting in a loss of approx. €873,000 year^{-1}. This totals more than €8.7 million for the 10 years evaluated, based on 2023 sales prices (1.73€ kg^{-1}). Peach production is important for Türkiye, and strict eradication projects are being carried out to attempt to prevent these losses.

Plum production is modest compared to other stone fruit varieties in terms of area, with cultivation occurring on an average of 21,342 ha. Green plum (*Prunus cerasifera*) has gained importance in the Aegean and Mediterranean Regions, on the sea coastlines. In the interior and transition regions, European (*P. domestica*) and Japanese (*P. salicina*) plums, along with cultivars suitable for storage and drying, are more common. All plum varieties had national production of 355,132 t in 2023. The impact of PPV on yields is estimated to be 0.1 %, resulting in a loss of €490,082 year^{-1}. This is valued at approx. €5 million in the 10-year period where presence of sharka was declared. Calculations were based on an average selling price of 1.38 € kg^{-1}.

For apricot, Türkiye produced approx. 22 to 25% of world apricot production, and ranks first in production. A significant portion of this production comes from the Malatya and Elazığ provinces, which contribute, respectively, 63.5% and 7.6% of the national apricot production. These two provinces have been designated as PPV-free regions, which results in a low impact of sharka for commercial apricot production in this country.

For almonds and cherry, there have been isolated sharka detections in almonds, but these plants do not exhibit symptoms (Akbaş *et al.* 2011). For cherry, PPV-T has been so far detected in a single plant, and no infections were found within a 10 km radius of this tree. Since 2019 approx. €30 support has been paid to the producer for each tree eradicated due to PPV (Coşkan et al 2022). The total number of eradicated trees from 2019 to 2023 has been approx. 2,000, so the amount paid to producers is approx. €60,000. The total estimated direct harvest losses due to PPV are approx. €13.7 million. The indirect costs associated with PPV and sharka management within the scope of the PPV-free area programme, is calculated to be €340,000, with the greatest proportion of total indirect costs related to tree eradication, analysis, and project expenses being ELISA tests at €209,000. Identification procedures are estimated to cost approx.

€38,000. Surveys carried out cost at least €54,583 (Birişik *et al.* 2021; Morca *et al.*, 2022).

In summary, the estimated indirect costs of sharka were almost €0.5 million, excluding commercial fruit losses. The direct and indirect losses are estimated to be approx. €13.5 million for 2014 to 2023, which is equivalent to an average of €1.35 million year^{-1}. This represents about 0.06% of the average annual value of production of apricots, peaches, and plums produced (estimated at approx. €2.325 thousand million).

Since the detected PPV strains are PPV-D, -M, -Rec, and -T, special attention and monitoring must be maintained to prevent potential sharka damage, which has not yet occurred to the robust Turkish stone fruit industry.

Case study for Chile

Chile is an important stone fruit producing country in the Southern hemisphere. In 2023, the value of the exported stone fruit from Chile was of €670,500,000. PPV was detected in 1993 (Acuña, 1993; Herrera, 2013), with PPV-D the only strain found since its initial discovery (Rosales *et al.*, 1998; Fiore *et al.*, 2010). Direct losses associated with sharka have been as follows:

For peaches and nectarines, the cultivated area of peach trees has been decreasing since 2003, while the area of nectarine trees has remained stable. The main reason for this situation is the shift towards cherry trees, which is currently the main stone fruit produced in Chile. However, Chile continues to be the main producer of nectarine peaches in Latin America and ninth in the world, with an estimated production of 312,907 t (FAOSTAT, 2023). The peach production is mainly dedicated to the canning industry, where sharka disease does not represent a major problem. Nectarines are produced for export as fresh fruit and therefore, the symptoms caused by sharka do represent a serious problem. However, there is no record of fruit losses or rejections associated with sharka in packaging warehouses in the interior of the country, probably because in general, farms dedicated to exports have strict control measures in place to minimize sharka symptoms. Currently, there are no official evaluations for losses in fresh market nectarines. However, it is here estimated that a loss of 0.05% is prudent, which is similar to that in other exporting countries. This is equivalent to a loss of 42.5 t per year, from annual production of 85,000 t and value of €1,288 per t. The estimated cost associated with sharka during the last 28 years is approx. €1.532 million.

Plum is the second most important stone fruit produced in Chile, with the European plum being the main cultivated type (14,316 ha), followed by Japanese plum (3,465 ha). In 2023, the industry exported 225,198.5 t of plums, with a value of €561,705,000 (FOB). Chilean plum production is estimated at 424,887 t (FAOSTAT, 2023), ranking fifth in the world and first in South America. The cultivated area for plum trees has shown sustained growth from 1997 (12,398 ha) to 2023 (17,781 ha), although the plum tree proportion relative to the total area of stone fruit trees has decreased, due to rapid expansion of sweet cherry production. There is no official estimation of plum losses, but these are here estimated to be approx. 0.05% of fruits, representing 212.4 t year^{-1} and value of approx. €9.247 million during 28 years (at a price of €1,555 t^{-1}).

Apricot cultivation showed has decreased in Chile, with the latest registry (2021) indicating 539 ha planted. Symptoms caused by PPV in apricots are severe, and investing in apricot trees is considered high-risk. Losses due to rejection of fresh fruit are here estimated at approx. 0.05%. Therefore, on national apricot production of 4,562 t with an average value of €1,834 t^{-1}, these losses represent 2.3 t year^{-1}, or €4,218 year^{-1}. Consequently, these estimated losses amount to approx. €118,104 in the period 1995 to 2023.

For almond and cherry, no fruit losses are currently associated with sharka.

Indirect costs associated with PPV are primarily related to the surveillance and sharka containment, which has been managed through official control measures directed by the Agricultural and Livestock Service (SAG). Official sharka control involves annual costs for the Chilean government and private companies producing stone fruit. Annually, nurserymen must declare the mother plants from which propagation material will be obtained, and these plants must be analyzed by laboratories recognized by the SAG. The costs of these analyses are borne by the nursery companies. Between 1995 and 2023, 423,150 official analyses were conducted using RT-PCR tests, except for in the early years of this period when the ELISA technique was used in combination with RT-PCR. The total cost of these analyses is estimated to be €2.556 million. Of the total analyzed plants, 0.29% tested positive for PPV, resulting in eradication of 1,232 plants at a cost carried by the private industry sector. The official PPV control regulation in Chile does not provide for compensation.

These costs, along with those associated with human resources for sample collection, and laboratory analyses, have estimated value of approx. €5 million. Additionally, the government of Chile, through SAG, invests human resources dedicated to orchard surveillance and ensuring compliance with disease control regulations. For the period between 1995 and 2023, this investment is estimated to be €10.384 million including laboratory analyses (ELISA and RT-PCR) by SAG laboratories for samples collected during orchard surveillance and surveys. In addition, the Government of Chile invested €940,000 primarily for epidemiological studies and for PPV strain identification. Only PPV-D has been detected, which has left cherries unaffected. Cherry is the main stone fruit exported from Chile, accounting for 56.9% of the total volume of exported stone fruit during 2023. The approx. annual total value of plums and peaches/nectarines produced in Chile is €670.447 million (Chilean customs, 2020).

In summary, the total estimated direct costs of sharka in Chile exceed €12.298 million, with main indirect costs totalling approx. €13.890 million associated with sharka management in that country (excluding indirect trade losses, and costs for administrative procedures). Together, these losses amount to approx. €26.188 million for the period 1995-2023. This equates to almost €1 million per year, representing approx. 0.14% of the average annual value of peach/nectarine and plum production in Chile in 2023.

Case study for Greece, where sharka is endemic

Stone fruit trees are the most important fresh fruit trees in Greece, occupying 67,000 ha and producing 1,124,000 t, with peaches and nectarines accounting for 80% of these totals (FAOSTAT, 2023). PPV was first reported in Greece in 1967, and within 10 years, PPV became widespread in areas of intensive Prunus cultivation, with apricot being the most affected. The Grecian share of World production of processed apricots diminished from 35% to 13% in 1995 (USDA/FAS). Widespread PPV occurrence led to the implementation of an eradication programme in the late 1980s, resulting in the disappearance of traditional apricot early-sensitive cultivars (e.g., ‘Early of Tyrinth’, and ‘Diamantopoulou’) of excellent quality and flavour, and considerable reductions of the cultivated area and production, particularly of apricots. Natural infections of almonds have been recorded (Kaponi *et al.*, 2012), but without consequences for production. The virus has not been detected from sweet or sour cherries, cultivation of which has doubled in the last 25 years. The majority of Greek PPV isolates have been classified as PPV-M and particularly belonging to the Ma clade of Mediterranean isolates, although there have been a few cases (three of 28) where PPV-D isolates were identified (Dimitriadou, 2015). Research projects to generate new tolerant varieties, evaluate the susceptibility of foreign varieties under local conditions, the modes of virus spread in the field, and PPV incidence in germplasm collections and nurseries, have been implemented for several years (Drogoudi and Pantelidis, 2017; Varveri, 2017). Considerable effort is being made regarding the production of PPV-free plant propagation material, and the immediate eradication of diseased trees in orchards, a practice often adopted by growers. Nevertheless, the economic damage of PPV on Prunus cultivation remains high and annual rejections of apricot and peach fruit during packaging are estimated to be at least 30% of the total production.

For apricot, as a result of the PPV eradication programme which started in 1988, the area cultivated in 1995 was 4,670 ha with production of 42,800 t, the lowest ever recorded in the country. Since then, production has increased 2.6-fold (112,000 t, FAOSTAT, 2023) due to cultivation of foreign tolerant varieties, and Greek varieties (e.g. ‘Tyrbe‘ and ‘Nostos‘) issued from national breeding projects of the Institute of Plant Breeding and Genetic Resources, at Naoussa. The currently preferred cultivars are ‘Mogador’, ‘Mirlo Blanco’, ‘Pricia’, ‘Lilly cot’, and ‘Wondercot’. The PPV-sensitive variety ‘Early of Tyrinth’ currently occupies 580 ha, only 6% of the total apricot area [Greek Payment Authority of Common Agricultural Policy (C.A.P.) Aid Schemes-OPEKEPE, 2023]. Old local varieties of intermediate susceptibility, such as ‘Bebecou’, are still cultivated (2,160 ha, OPEKEPE, 2023) for their preferred characteristics, particularly as processed product (pulp or canned fruit), although the lifetime of cans is reduced to 3 years due to PPV. Rejections during fruit packaging are estimated at about 35% of the production, totalling approx. 39.2 tons per year. At €0.59 per kilogram, this implies direct losses of more than €23 million per year.

For peach and nectarine, quality of peaches is also affected by PPV, the main problem being softening of the fruit. Peach production has diminished principally for commercial reasons, particularly in the last 10 years. In 1995, the area cultivated with peach and nectarine trees was 53,504 ha with production of 1,034,400 t, but currently these crop areas have diminished to 38,220 ha and production of 894,510 t, a production reduction of 13.5% (FAOSTAT, 2023). Early peach cultivars (e.g., ‘François‘, ‘Lolita‘) are the most susceptible to PPV, exhibiting symptoms on 50-65% of their fruit, which are rejected during fruit packaging, and these cultivars are being replaced by late ripening ones. The overall rejections of late varieties during packaging are estimated at approx. 30% of peach production each year (direct losses of about €26,8 million year^{-1} at value €0.10 kg^{-1}). Studies conducted at the Institute of Plant Breeding and Genetic Resources evaluated the PPV resistance of different peach and nectarine cultivars, identifying tolerant varieties such as ‘Tasty Free’, ‘Jerseyland’, ‘Gialla Precoce Morettini’, ‘Desert Gold’ and ‘Springtime’.

Plum production is less important in Greece than other stone fruit, but has been steadily increasing. In 1995, the area cultivated with plum trees was 719 ha with a production of 3,737 t, but at present these have increased to 2,140 ha and 24,380 t, a production increase >550% (FAOSTAT, 2023). The 'Angelino' Japanese plum cultivar, which is moderately sensitive to PPV, is the most common, covering more than 25% of the total plum tree cultivated area. Annual fruit rejections during packaging are estimated at around 11% of the production (direct losses of about €1.4 million/year at a price of €0.54/kg).

The losses in Greece due to sharka outlined above show that this disease has significant economic impacts on the stone fruit industry in that country. These total approx. €51 million per year.

Costs due to sharka in world Prunus industry

The presence of PPV and management of sharka in the 54 countries that have officially declared presence of the virus, including efforts toward eradication, indicate that this disease has considerable international economic impacts. An accurate international evaluation of the associated costs to Prunus industries is difficult, due to uncertainties in estimating actual direct crop losses due to the disease. This is especially relevant due to the weight and influence on the final estimation of the associated losses in China, where Prunus production and marketing have become major industries. Estimation of real direct losses is also difficult due to the different approaches to PPV management in different countries. For example, central European countries where PPV is endemic, unlike recently or locally infested countries, do not perform PPV eradication programmes but rely on cultivation of tolerant Prunus genotypes. Also, there are no available and accurate data on the actual sharka impacts from some territories, so erroneous estimations for these areas could lead to unreliable conclusions. Therefore, conservative estimates have been made in the following sections of this review, addressed by crops, and also considering the PPV strains present in each country, the actions or programmes available in the literature, and information supplied by expert colleagues and personnel from national Plant Health or Plant Protection Services. These general data are summarized in Table 1.

*Common apricot (*Prunus armeniaca*) and Japanese apricot (*P. mume*)*

Apricot, alongside the European plum, is the most fruit type affected by sharka (Martínez-Gómez *et al.*, 2000). According to FAOSTAT (2023), the greatest apricot-producing countries where PPV has been detected (based on historical data), are: Türkiye (one of the largest producers of apricots), Iran, China (a world leading apricot producer), Uzbekistan (the major apricot-producing country in Central Asia), Italy: (a prominent apricot producer in Europe), and Spain and France (high-quality producers of apricots). The main Prunus producers with declared PPV presence are (in alphabetical order): Argentina, China, Cyprus, Canada, Croatia, Egypt, France, Germany, India, Iran, Israel, Italy, Japan, Jordan, Kazakhstan, Mexico, Pakistan, Portugal, Russia, Spain, Syria, Türkiye, Tunisia, Uzbekistan, and Ukraine, with an estimated total average global production of 2,320,000 t. Due to uncertainties about actual production in these countries, the present study uses a conservative average of 2% of fruit rejected, which represent approx. 46,400 t. With an average price of €0.30 kg^{-1} for fresh or dried fruit in pallets of 100 kg, this represents €13,920,000 year^{-1}, indicating, over the last 28 years, accumulated losses of approx. €389,760,000. This amount must be added to the losses incurred in countries where PPV-M is prevalent and other PPV strains causing more damage are also present, estimated at an average of 5% of the total apricot production. These countries include Albania, Bulgaria, Bosnia and Herzegovina, Greece, Moldova, North Macedonia, Poland, Romania, Serbia, Slovakia, and Slovenia, with a combined estimated production of apricots of approx. 418,200 t. With estimated losses of 20.91 million kg at an average price of €0.30 kg^{-1}, this represents annual losses of €6,273,000, amounting to approx. €175,644,000 over the period 1996 to 2023. Consequently, the total direct costs for apricot losses associated with sharka during this period amount to approx. €565,404,000 (Table 1).

*Japanese, Chinese plums (*Prunus salicina*) and European plums (*P. domestica*)*

Japanese and Chinese plums dominate world fresh fruit markets whereas European plums are also common in some regions, mainly in Europe, America, and Asia (FAOSTAT, 2023). Since China, especially Sichuan province, is the largest producer these plum species (Liu, 2018), accounting for almost 58% of the world plum production, that country should have the greatest weight in estimation of losses due to sharka. However, uncertainty is high related to Chinese production and the prevalence of PPV.

PPV-D symptoms on Japanese plums are rare, although the virus reduces numbers of marketable fruit. Conversely, incidence of sharka on *P. domestica* is important in Europe where PPV-M is the prevalent strain. For plums, evaluation of losses has been carried out based production and the local presence of specific PPV strains in production regions.

The European Union (EU), particularly central and eastern Europe, is where major losses have been associated with sharka in European plum, and the diseases is also important in Southern European and Mediterranean countries, where Japanese plums predominate. Direct losses of 5% are estimated in the demanding plum markets of the European Union. In an average world production of 1,300,000 t, losses due to sharka would represent 65,000 t of fruit rejects per year, with a value (at €0.5 kg^{-1}) of €32,500,000 year^{-1} in the EU (€910 million from 1996 to 2023) (Table 1).

The second area with direct fruit losses associated with sharka is China, where estimated 0.1% of rejects due to the disease is here made, with uncertainty due to lack of reported data. This would represent 6,700 t loss from production of 6.7 million t, which at a local price of €0.2 kg^{-1}, would cause losses valuing approx. €1,340,000 year^{-1} (€37,520,000 assuming PPV has been present since 1995).

Ranking third is a group of countries which include (in order of plum production): Serbia, Iran, Türkiye, Chile, India, Ukraine, Russia, and Uzbekistan. This group have combined annual plum production estimated at 2,600 t. Sharka could cause losses, estimated on a country-by-country basis, of 79.56 t annually, valued at €39,78 year^{-1}, which totals €1,113,840 for 1996 to 2023.

The countries with least plum production are Mexico, Moldova, Bosnia and Herzegovina, Kazakhstan, Argentina, Turkmenistan, Syria, Israel, Armenia, and North Macedonia (ranked by decreasing amounts produced). Their combined production is approx. 464 t. It is here estimated, with uncertainty, that these countries could experience direct fruit losses of approx. 8.66 t annually, with an estimated value of €4,330/year, totaling €121,240 from 1996 to 2013.

Total world direct losses caused by sharka in plum production are estimated at €33,884,110 year^{-1}, equivalent to €948,755,000 for 1996 to 2023 (Table 1).

Peaches

Peaches (*Prunus persica*) suffers minor losses from infections of the predominant PPV-D strain (Samara *et al.*, 2017). However, the amount of fruit rejected could be significant in areas where other strains of PPV are present. In areas where peach production is primarily focused on canning industries, sharka does not pose major problems. The top ten countries where peach production is most concentrated, and where PPV is present, have substantial average production volumes. These countries, in order of annual peach and nectarine production during 1996 to 2023 are: China (13 million t); followed by Spain and Italy (totalling 2 million t); the USA (0.8 million t); Greece (0.8 million t), Türkiye (0.7 million t), Iran (0.4 million t), Egypt (0.36 million t), Chile (0.33 million t), and Argentina (0.24 million t). Their total annual peach production, excluding the USA (where PPV was eradicated), is 17.83 million t. In addition, PPV is present in other important peach producing countries, such as: India (0.24 million t) and France (0.2 million t), totalling peach production 0.44 million t per year. Consequently, production of peaches is at least 18,270,000 t each year in countries where sharka occurs. Estimated losses due to the disease of 0.025% (because peaches showing superficial symptoms can be used peeled for canning, and only nectarines are rejected), could cause 45,675 t of discarded fruit, amounting to economic losses of approx. €18.32 million year^{-1} at an average estimated cost of €0.4 kg^{-1}. From 1996 to 2023, these losses could total approx. €511.56 million (Table 1), which does not include costs of the mandatory sharka eradication programmes adopted in Canada and USA.

Cherries

The top ten producers of sour cherry (*P. cerasus*) and sweet cherry (*P. avium*) are Türkiye, Chile, Uzbekistan, USA, Spain, Italy, Iran, Greece, Poland, and Syria. These countries produced, in 2022, approx. 75% of world cherries. Including other producers, the average annual production during 2008-2022 was approx. 2.35 million t (FAOSTAT, 2023; Palmieri, 2024). Among the PPV strains that severely affect both cherry species, PPV-C has been found in Russia, Moldova, Germany, Italy, Hungary, Croatia, and Belarus. PPV-CR and PPV-CV have been detected only in Russia (estimated annual cherry production of 294,000 t) (FAOSTAT, 2024). PPV-C can reduce the productivity of some *P. cerasus* cultivars and hybrids by 38 to 45% (Sheveleva *et al.*, 2021). These losses were obtained from 152 fruit-bearing sour cherry trees in the Tatarstan region of Russia, so they are an uncertain basis for determining generalized sharka losses for sour cherry production. Nevertheless, neither premature fruit drop nor sharka fruit symptoms are observed on sour cherry in Russia, although the disease probably causes losses, but these have not been precisely evaluated.

Almonds

No losses due to sharka have been reported from any country where almond (*P. dulcis*) trees are grown and the disease sharka is present, even in endemic situations.

CONCLUSIONS

The estimated total world costs of €2,394,119,080 (approx. €2.4 thousand million; '€2.4 billion') (Table 1) associated with the prevention and management of PPV and sharka from 1995 to 2023, despite the high value, indicates a significant reduction compared to the €10 thousand million incurred in previously evaluated period from the 1970s to 2006 (Cambra *et al.*, 2006a). Cumulative world losses from the sharka pandemic since the decade of 1910 to 1920 should surpass €13 thousand million in nominal terms (without inflation adjustments). The first evaluated period was 30 years up to 2006, characterized as the most severe period of sharka in Europe and onset of the disease in America and Asia. During that period, social and political impacts of the disease were severe (Capote *et al.*, 2006; Damsteegt, 2008; Barba *et al.*, 2011; Sochor *et al.*, 2012), with significant loss of biodiversity in traditional fruit cultivars across Europe. At that time, current detection and diagnostic methods and kits were not available or commonly used on large scales (Cambra *et al.*, 2011), and the trade and traffic of plant material was frequent, especially between neighboring countries, but also over long distances, in an expanding fruit production industry.

The reduction in costs related to PPV indicates improvements in sharka management practices (along with other possible factors) have contributed to reducing the economic effects of PPV and sharka. Based primarily on the reports of Gottwald *et al.* (2013), Welliver *et al.* (2014), Rimbaud *et al.* (2015), García *et al.* (2014; 2024), the major factors that have collectively contributed to the reductions in these economic impacts from 1995 to 2023, compared to 1970 to 2006, were:

Advances in disease management:

- Improved prevention, eradication, and integrated control methods;
- Use of more PPV-tolerant cultivars and PPV-free nursery plants;
- Enhanced monitoring and quarantine measures;
- Effective eradication or reduction of PPV inoculum in key areas.

Technological improvements:

- Development of more accurate and rapid diagnostic tools;
- Enhanced sampling methodologies for large-scale pathogen testing;
- Early detection facilitating timely intervention and containment.

Education and awareness:

- Increased awareness and education in PPV prevention and management among farmers, nurserymen and stakeholders.
- Improved knowledge and legislative framework leading to better disease management and reducing illegal plant material traffic.

Support and co-operation:

- National and international support for research, surveillance, and control programmes;
- International co-operation facilitating dissemination of best practices, and co-ordinated efforts through common research projects, networks, and international diagnostic standards.

Industry adaptation:

- Diversification of production, such as increasing cherry cultivation in areas without cherry-adapted PPV isolates, facilitated by more favourable market conditions for expanding cherry production.
- Investment in disease-resistant/tolerant cultivars developed through different conventional and new technologies;
- Implementation of rigorous phytosanitary measures and improved nursery practices.

Nevertheless, the evaluated total cost of €2.4 thousand million from 1996 to 2023 is significant. This represents approx. 0.17% of the value of the stone fruit industry (average annual estimated value of production for 1995 to 2023 approx. €51 thousand million), according to FAO. These costs are likely affected by increased globalization and the interconnectedness of economies, which have facilitated the spread of sharka to new regions, often through uncontrolled movement of PPV-infected plant material. Additionally, lack of effective control measures and efficient biosecurity practices in many areas have allowed sharka to persist and spread, thereby exacerbating the economic impacts of the disease. Overall, the factors that have contributed to these substantial costs, can be summarized as follows:

- **Continued spread of PPV:** Despite control measures, PPV has persisted in many regions, requiring ongoing application of disease management.
- **Aphid vector transmission:** PPV has continued to spread locally through aphid species vectors, necessitating constant insect monitoring and control, especially in plant nurseries.
- **High direct losses:** Significant losses from unmarketable infected stone fruit, especially European plums, has severely impacted the industry.

- **Indirect costs:** Ongoing expenses for sample collection, ELISA and PCR-based testing, surveys, research, and control strategies.
- **Expensive eradication and containment programmes:** The difficulties and costs of PPV eradication and the lack of success in many areas, require integrated and costly containment measures that frequently result in maintenance of pathogen inoculum.
- **International trade restrictions:** The rejection of sharka symptomatic fruit in international markets, and precautions and careful selection to avoid export of symptomatic fruit.
- **Research and development:** Continued investment in research and scientific networks to develop disease management strategies and resistant or more agronomically tolerant cultivars, along with the costs of field trials.
- **Exclusion of certain costs:** This study did not account for trade costs, genetic erosion of traditional cultivars, loss of biodiversity, research and development for PPV resistant/tolerant cultivars, or measures to prevent and avoid PPV entry in certain areas, including the implementation of phytosanitary controls at entry points and legal frameworks, indicating additional hidden impacts.

Investments made in each country for sharka management, usually but not always, align with national significance as producers and exporters of stone fruit, aiming to maintain competitiveness in increasingly demanding markets, and to ensure the future for the respective fruit production industries. For instance, primarily in Southern European Union countries, such as Italy, France, and Spain, significant economic efforts have been made to contain sharka, which in Spain's case represents about 0.32% of the average annual value of apricot, peach, and plum production. Furthermore, with PPV being downgraded to RNQP for the European Union (EU regulation 2016/2031), the future may be more uncertain, as private control is usually less or non-effective for successfully managing sharka (Martinez *et al.*, 2024). In other countries, despite investments in containment, and considering PPV as a quarantine pest, the efforts have not been sufficient in relation to the total values of stone fruit production and the quantities of exported fruit. Robust programmes to manage sharka are needed in high-value stone fruit industries. Countries with less significant stone fruit industries probably invest less in disease management, posing risks for other areas by maintaining PPV reservoirs, from which infected material could be illegally transported (for cultural or traditional reasons) to other regions or countries where PPV and sharka is effectively contained, or has been eradicated.

Distribution of total losses due to PPV across regions for 1995 to 2023 reflects the extent of the regions. Asia experienced the largest total economic losses and associated costs (direct and indirect). Europe and the Americas together had similar losses despite the large differences in land use and agricultural practices in these regions. The African continent, despite risks of PPV introduction, probably applies the lowest costs for prevention. As the region with least land area, Oceania accounts for the lowest indirect total associated economic losses, which are mainly devoted to efficient prevention of PPV entry and establishment.

An uncertainty for estimating costs is the value applied to losses associated with sharka. Fluctuations in stone fruit prices can be caused by several factors, including supply and demand. Increases in agricultural input and labour costs can also impact fruit market prices, as well as competition, especially in case of oversupply. Government interventions, including tariffs, agricultural subsidies, and trade regulations, can also impact stone fruit prices. combinations of these factors, and others, cause variable markets prone to abrupt fluctuations. However, once fruit losses were estimated in this study, with uncertainties in some cases due to lack of transparency in officially acknowledging the losses where these have not been published, they were assigned value likely to be appropriate. Sharka affects trees differently in each stone fruit production area, depending on PPV strain(s) and the predominant or majority strain(s). Yield losses in infected cherry trees have been reported, but it is difficult to establish exact loss amounts. Accurately determination of these losses has yet to be achieved, as the pathogen strains must be prevented given the substantial growth in cherry cultivation.

Resilience through the use of ′agronomically tolerant cultivars′ (e.g., domestic plum cultivars produced at the Fruit Research Institute at Čačak in Serbia) is being pursued in Central and Eastern Europe, in areas where sharka is endemic. The PPV-resistant, genetically engineered HoneySweet cultivar was deregulated in 2007 in the USA, after numerous international field trials and analytical assays, and was released to breeders and growers concerned about the threats of PPV (Scorza *et al.*, 2007). This or a similar engineered cultivar has not yet been approved for release in the European Union.

The combined use of certified virus-free plants, even those sensitive to PPV, produced in approved nurseries, along with multiplication of PPV-resistant or tolerant cultivars, is allowing the maintenance of stone fruit production in countries where sharka has not been eradicated.

Research efforts on PPV must remain active and innovative in several topic areas, such as in advanced diagnostic and detection techniques, sampling methodologies for eradication, or accurate testing to determine the PPV-free status of plant material, as well as plant-virus interaction studies aimed at interfering with virus spread. Establishment of certification programmes for *Prunus* spp. should be globally promoted. Consistent and durable financial support for advanced technical and scientific assistance to the Prunus industries is advisable, proportional to the value of the industry in each country. Active dissemination through educational programmes should emphasize the imprudence of moving plant material without comprehensive sanitary guarantees. Urgent development and application of conventional, transgenic, or genome-editing techniques to obtain tolerant or, preferably, resistant stone fruit cultivars (Cirili *et al*., 2016; De Mori *et al*., 2020; García *et al*. 2024) are also important for sharka disease management, and should be strongly promoted.

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