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Estimating tomato production losses due to plant viruses, a look at the past and new challenges

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Abstract

This review analyzes the available technical and scientific reports addressing tomato crop losses and discusses the ponderable characteristics for estimating losses caused by Tomato Infecting-Viruses. The tomato around the world represents an important economic aspect, it has been positioned as a crop that contributes to the gross domestic product and is essential to achieve food security in some regions. Viral diseases are one of the main causes of economic losses and tomato production, due to the easy dissemination of viral particles, difficult detection, and the few options to combat virus diseases. Tomato Infecting-Viruses such as ToBRFV, TLYCV, TSWV, and TMV are some of the most important viruses due to their ability to cause losses. Abiotic factors must be considered to estimate losses with greater precision and biotic factors, restricted mainly to insects, have an important role in the virus dispersion and adaptation to new niches not studied yet. Viral infections in tomato crops can reach 100% and reported losses are between 2 and 10%. There are no recent official statistics on economic losses due to tomato viruses, the main limitation is to extrapolate and accurately predict today's losses with data from the past decade. The main challenges for estimating the economic impact of viral diseases in tomato crops lie in the omission by growers and authorities on the presence of viral symptoms and the product value in the market. Considering the absolute value of tomato cultivation economic losses by virus diseases should be around 2 to 5% annually.

Keywords: crop, losses, tobamovirus, tomato

Introduction

Tomato is positioned as a fundamental crop to achieve food security in the countries (Pathak and Stoddard, 2018). According to the Food and Agriculture Organization (FAO) tomato production worldwide has maintained sustained growth for more than 15 years, only in 2020 more than 186 million tons of tomatoes were produced, with a yield of 37 tons/ha (FAO, 2023). For over a decade, China, India, and the United States have been at the forefront of the production and export of fresh tomatoes.

Large-scale tomato production has experienced significant growth due to the development of cultivation techniques, technology introduction, and plant breeding which has allowed the appearance of new varieties to satisfy market demands (Mata-Nicolás et al., 2020). The severity of diseases caused by these biological agents is worsened by the reduction of cultivars used in farming systems, which narrows the germplasm base and reduces the genetic diversity increasing susceptibility. Currently, the main challenges for tomato production consist in reducing the economic costs of inputs and making the practice profitable through the application of agricultural technologies that increase production efficiency and allow higher yields to be obtained.

Diseases caused by bacteria, fungi, and viruses are established as the main cause of economic and production losses in tomato cultivation (Wenig et al., 2022; Campos et al., 2022). However, the interest in understanding the nature of viral infections is notable due to the few available solutions and combat methods (Salas-Gómez et al., 2022). Virus diseases affect growers and consumers in two ways. First, the time consumed in estimating the spread of the disease may be critical between restricting the outbreak or declaring infection and total loss of the crop; and second, the presence

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of visible signs of viral symptoms in the fruit (spots, discoloration, other traits), which undoubtedly reduces the economic value of the product, impacting the purchase-sale price.

The tomato crop is affected by a wide variety of virus families, varying in importance by the genus to which they belong (Hančinský et al., 2020). Tomato spotted wilt virus (TSWV), transmitted by thrips; tomato yellow leaf curl virus, (TYLCV), transmitted by the whitefly *Bemisia tabaci*; and tomato brown rugose fruit virus (ToBRFV), classically spread by mechanical transmission (Margaria and Rosa, 2015; Prasad et al., 2020; Salem et al., 2022) they are viruses that historically cause losses in tomato crops.

Although scientific reports have focused on describing the presence of different Tomato Infecting-Viruses (TIV) and the virus-plant interrelationships, the analysis of relevant aspects related to the economic losses and damage to tomato crop production due to viral infections seems neglected. The purpose of this review is to analyze the available technical and scientific reports addressing tomato crop losses and discuss the ponderable characteristics for estimating losses by TIV.

Tomato cultivation around the world, implications for yield improvement

Solanum is the largest genus in the Solanaceae family, encompassing approximately 1,700 species (Bergougnoux, 2014); *Solanum lycopersicum*, also known as cultivable tomato, is the most important species of this genus. Thus, tomato cultivation not only satisfies a food need but also has a direct and positive impact on the economy of countries worldwide; **Table 1** describes key economic aspects of the main tomato-producing countries.

The World Processing Tomato Council (WPTC) reported a slight decrease in tomato crop production in the past recent years due to factors such as water availability, soil characteristics, and changes in weather conditions. However, an estimated increase in the processed tomato market for the coming years highlights the need for strategies to overcome such disparities between tomato crop production capabilities and demand. In 2022, tomato global production reached a volume of almost 80 million tons, and it is expected that between 2023 and 2028 it could reach 100 million tons (WPTC, 2022). For a long time, the addition of organic substrates has been a way to provide nutrients to tomato plants, from organic fertilizers, urea addition, and composts to fertilizers that supply the nutritional needs of the plant. Innovative agricultural practices have been implemented to achieve sustainability in the cultivation of vegetables. Jeger (2022) emphasizes the role that water and other elements could play in virus-plant interactions; and Chouchane et al., (2018) expose that the availability of irrigation water in the world is a limitation to achieving food self-sufficiency which negatively impacts the yields of important crops such as tomatoes. According to current forecasts, by 2050 food will have to be produced for 9 billion people around the world. (Hussain et al., 2020). Under this argument, various strategies in the use of water have been evaluated with the premise of being able to be extrapolated to the tomato crop.

Paul et al., (2019) evaluated the ability of Plant-Derived Protein Hydrolysates (PHs) as a stimulant capable of increasing plant growth and crop yield. After foliar and drip application of a limited amount of water in

Table 1. Main economic aspects related to countries producing tomatoes

Country	Agriculture to GDP	Tomato production, Million tons. (year)	Tomato cultivated area Thousand ha. (year)	Reference
México	3.4%	3.4 (2022)	45 (2020)	Montaño-Méndez et al., (2021) SIAP, (2022)
U. S. A.	5% (Farms 1.4%)	11 (2019)	160 (2019)	USDA, (2021) STATISTA, (2023 a) STATISTA, (2023 b)
Turkey	6.4%	13 (2022)	415 (2018)	Tomato Days, Turkey (2022) Global trade (2020)
China	7.3%	64 (2020)	1,100 (2020)	STATISTA, (2023 c) Tomato news (2022)
Italy	2%	~1 (2021)	25 (2021)	STATISTA (2023 d) Gambuzza (2022)
India	19% (GVA)	20 (2023)	852 (2021)	Indian Economic Survey (2022) STATISTA (2023 e) Horticulture Statistics (2021)
Spain	2.4%	4.2 (2020)	55 (2021)	STATISTA (2023 f) STATISTA (2023 g) EUROSTAT (2022)

GVA: GVA= Gross Domestic Product + Subsidies on products – Taxes on products.

tomato crops, it was found that plants treated with PHs showed changes in biomass accumulation and the metabolic profile showed greater tolerance to oxidative stress compared to untreated plants. Aires et al., (2022) demonstrated that the foliar application of salicylic acid in tomato crops with water deficit reduced flower abortion and increased fruit production compared to controls. Novel approaches using silicon matrices have also been evaluated as agents that improve tolerance to water stress in tomatoes. Shi et al., (2016) evaluated the effects of silicon on water uptake and its role in reducing oxidative damage in relation to root hydraulic conductance. Concluding that the addition of silicon in tomato plants improves tolerance to water stress by improving the hydraulic conductance of the roots and the absorption of water in tomato plants. Other approaches that have been evaluated establish the use of microorganisms such as fungi and bacteria (Bowles et al., 2018; Volpe et al., 2018; Riva et al., 2021), abscisic acid (Li and Liu, 2021), biochar (Guo et al., 2021), even effluent from fish farming (Alvares da Silva et al., 2022). Most of the previous strategies have the implicit objective of saving water, for the moment they are in the evaluation stage, and little is known about their extensive use. Undoubtedly, these innovative methodologies may be useful in the future for saving water in vegetable crops in general.

Preponderant biotic and abiotic factors in the spread of plant viruses

It is difficult to estimate the impact caused by plant viruses on crops, without considering environmental factors. Water, soil, and air are important ways for plant virus dispersion, but climate change is a preponderant factor in the spread of viruses and is closely related to economic losses in crops (Jones, 2016; Pallas et al., 2018). The fluctuating temperature, long droughts, and the change in rainfall patterns factors brought about by climate change directly contribute to the agricultural yield of various crops including tomatoes (Ullah et al., 2019; Bhusal et al., 2022). Subsistence methods and adaptation to climate change in crops such as tomato consist of intercropping and adjustment of crop planting, combination of inputs (Abid et al., 2016), building living walls, reforesting (Shinbrot et al., 2019) and even education and experience of growers (Irham et al., 2022). Natural formations such as mountain ranges, seas and other types of geographical situations that allow separating territories are considered preponderant aspects for the control of the spread of viruses that infect plants, especially TIV. (Rodoni, 2009; Jones, 2021). On the other hand, biotic factors are represented by organisms such as insects as propagation factors. As hosts, some insects are reservoirs of viruses involved in the appearance of new phenotypes of some virus families. A clear example is the versatility of the Begomovirus family, which through intra-genetic recombination allows genetic variability and speciation of the viruses that infect plants (Anwar and Tahir, 2018; Yin and Xu, 2023). These new findings are solid evidence of virus evolution completing its adaptation to new niches not studied yet.

The economic impact of diseases caused by TIV

Precise estimates for the yield impact of a pathogen on a crop may be inconsistent or even invalid (Sastry, 2013), but must be conducted to develop virus containment strategies.

Pathogens such as viruses are microscopic infective agents capable of disseminating their genes in host cells (Forterre and Prangishvili, 2009) and are responsible for a diversity of diseases that in extreme cases lead to the spread of significant epidemics or pandemics that affect crops of global importance for food security, for example, maize, wheat, rice, potato, banana, tomato, and others (Briddon and Stanley, 2006; Jones, 2021). In tomatoes, virus diseases are limiting factors for development and production (Souiri et al., 2020). Among viruses infecting tomatoes TSWV, TYLCV, and tobacco mosaic virus (TMV) have remained current for more than 100 years (Scholthof et al., 2011) and new viruses have been identified with the advancement of genomics sciences and new sequencing tools. Only from 2011 to 2021, up to 45 new species of viruses that infect tomato were reported (Rivarez et al., 2021), establishing a new panorama in terms of understanding the virus-plant relationship. For instance, the recent appearance of ToBRFV, a virus with scarce combat options that is present worldwide due to globalization and especially to the commercialization of infected seed, has caused a huge economic impact and represents a current challenge for global tomato production (Zhang et al., 2022). An updated list of alerts by country for viruses in tomato crops can be consulted in the EPPO Global Database (EPPO, 2023); and **table 2** describes current reports of economic losses due to the presence of viral diseases in tomato crops.

Plant breeding has brought with it the incorporation of notable characteristics to the tomato fruit, increasing yields, avoiding unwanted traits, and above all, presenting resistance to various pathogens. Previously, the introgression of genes such as *N*, *Tm*-2^2 or *Sw*-5, in tomato specialties allowed combating a wide variety of viruses such as TMV, ToMV, or TSWV (Lanfermeijer

Table 2. Reports around the world in the last 5 years (2017-2022) on economic and production losses in tomato crops derived from the appearance of viral diseases

Virus related	Disease detection	Year	Location	Infected area*	Losses (1) or infection (2) reported	Reference
PepMoV	TAS-ELISA and RT-PCR	2017	Punjab, India	1 Farm	(2) 25 %	Sharma et al., 2019
ToBRFV	dot-ELISA	2020	Tartous Governorate, Syria	Tartous and Lattakia regions	(2) 43%	Hasan et al., 2022
TBRV	Greenhouse evaluation by RT-PCR	2015	Riyadh region, Saudi Arabia	7 greenhouses	(2) 53%	Al-Shudifat et al., 2021
TSWV and other 18 different virus	Surveys and sample analysis by dot-ELISA and RT-PCR	2013-2017	Yunnan Province, China	12 cities	(2) ~100%	Li et al., 2021
ToBRFV	Greenhouse evaluation by RT-PCR	2018	Sicilian Provinces, Italy	100 greenhouses	(2) 40-100%	Panno et al., 2020
TCSV	Greenhouse evaluation by RT-PCR	2018	Florida U.S.A	~50 ha	36%	Poudel et al., 2019
ToLCNDV	Viral sequencing	2021	Zhejiang Province, China.	0.5 ha	Not available	Li et al., 2022
PepMV	Greenhouse evaluation and viral sequencing	2020	Jeolla Province, South Korea	1 greenhouse	(2) ~5 %	Cho et al., 2022
SLCCNV	Viral sequencing	2020	Shandong Province, China.	1 greenhouse	Not available	Qiu et al., 2022
ToBRFV	Greenhouse evaluation by RT-PCR	2019	Sinaloa, México	5 greenhouses	Not available	González-Concha et al., 2021
ToBRFV	RT-PCR and inmunocromathograpy	2022	Sonora State, Mexico	4 greenhouses	(2) 60%	Sánchez et al., 2023
ToBRFV	Greenhouse evaluation by RT-PCR	2018	Southern California, USA.	1 greenhouse (~8 acres)	Not determinated	Ling et al., 2019
TSWV, PhCMoV, ToTV, STV, And SpLV	Greenhouse evaluation and viral sequencing	2015	22 districts of Serbia	136 localities	(2) some localities with total losses	Vučurović et al., 2021

*Note: Pepper mottle virus (PepMoV); Tomato black ring virus (TBRV); Tomato chlorotic spot tospovirus (TCSV); Tomato leaf curl New Delhi virus (ToLCNDV); Pepino mosaic virus (PepMV); Squash leaf curl China virus (SLCCNV); Physostegia chlorotic mottle virus (PhCMoV); southern tomato virus (STV); and spinach latent virus (SpLV).

et al., 2003; de Oliveira et al., 2018). Nowadays, the appearance of new strains, viral outbreaks, or even new viruses such as ToBRFV has led to the introduction of improved tomato varieties to the market to meet new demands in terms of resistance. **Table 3** describes the main tomato varieties available in the commercial market with intermediate or full resistance to viral diseases, including the status of the most recent ToBRFV-resistant varieties and those resistant to multiple viruses, such as the ToMV-TMV-resistant varieties.

A hypothesis that could establish a range for the economic impact of the virus on tomato crops was proposed by Sastry et al., (2013) "*Worldwide economic damages caused by viruses in crops* (all) *are difficult to estimate; however, rough approximations indicate yield losses range from 30 to 50 billion dollars annually*". Recently, a survey of growers in the USA reported economic losses of approximately 17 million dollars annually attributed solely to ToBRFV infections (IUNU team members, 2022). The fresh tomato agribusiness in the USA was valued at 1.2 bn US dollars in 2015 (Kelley et al., 2020; USDA, 2016), and Capobianco-Uriarte, (2021) described the international tomato trade as valued at 8.5 billion US dollars. Before these reports, Hanssen et al., (2010) estimated that in 2007 the worldwide tomato market value was 30 bn US dollars; and recently in 2018, a World Tomato Market report estimated worldwide income for tomato at 190 bn US dollars (World Tomato Market Report, 2023).

Under the above parameters, it is impossible

Table 3. Commercial tomato varieties with virus resistance

Tomato class	Variety	Resistance traits*						Developer and reference
		ToBRFV	TSWV	TYLCV	ToMV	TMV	ToTV (a) ToANV (b)	
Beef	Ibeth	0	0	0	na	0	na	Fernández A (2022); Syngenta Seeds (2022)
	Patriarca	na	1	0	1	1	na	
	Sivinar	na	1	0	1	1	na	
Cocktail	Jawara	na	1	0	1	1	na	
Kocktail	Amelioso RZ F1	1	na	na	1	na	na	Rijk Zwaan Group (2022)
	Lucioso RZ F1	1	na	na	1	na	na	
	Valerioso RZ F1	1	na	na	1	na	na	
Medium TOV Cherry TOV Mini-Plum	Rexoso RZ F1	1	na	na	1	na	na	
	Sprioso RZ F1	1	na	na	1	na	na	
	Prospano RZ F1	1	na	na	1	na	na	
	Hyrule RZ F1	1	na	na	1	na	na	
	Rominetto RZ F1	1	na	na	1	na	na	
	Capuletto RZ F1	1	na	na	1	na	na	
	Parisetto RZ F1	1	na	na	1	na	na	
	Balthaseto RZ F1	1	na	na	1	na	na	
Saladette Rome Round	Azores	1	1	na	1	na	na	Enza Zaden Mexico (2022)
	Cedros	1	1	1	1	na	na	
	Arkoi	1	1	1	1	na	na	
	Toretto	na	na	0	1	na	1(b)	
	Socorro	1	0	na	1	na	na	
	Bosco	na	na	0	1	na	1(b)	
Grape	Haití	1	na	1	1	na	na	
	Ponza	1	na	na	1	na	1(b)	
	Pascua	1	na	na	1	na	1(b)	
Pear	Azovian F1	0	1	1	na	na	na	BASF (2022)
Cherry Round	Summer gem	na	1	1	na	na	na	Takii seed (2022)
	TI-09R	na	na	1	na	1	na	
	Luz 59	na	1	1	na	1	na	
	TTM-166	na	1	1	na	1	na	
Cocktail Plum Beef	FH201	0	na	na	na	na	na	TOTAM seeds (2022)
	TRS101	0	na	na	na	na	na	
	TRS102	0	na	na	na	na	na	
	GH601	0	na	na	na	na	na	
Pear	HP576 HF1	na	1	na	1	na	na	Gautier Group (2022)
	Corizia HF1	na	1	na	1	na	na	
Kocktail	K525	na	1	0	1	na	na	
Cherry Round	Melero F1	na	1	0	1	na	na	Ramiro Arnedo (2022)
	Pasadena F1	na	1	0	1	na	na	
Beef	Yeste F1	na	1	0	1	na	na	Fitó Seeds (2022)
	Vimeiro F1	na	1	0	1	na	na	
Round	Enate F1	na	1	na	1	na	na	
	Egara F1	na	1	na	1	na	na	
	Tores F1	na	1	na	1	na	na	
	Paladium F1	na	1	0	1	na	na	
	Molier F1	na	1	0	1	na	na	
	Eco Ateneo F1	na	1	0	1	na	na	
	Duratom F1	na	1	0	1	na	na	
	Carbonero F1	na	1	0	1	na	na	
Cherry	Manacor F1	na	1	na	1	na	na	
	Palamós F1	na	1	na	1	na	na	
Marmande	Maresme F1	na	1	na	1	na	na	
Cherry	HTL2008162	na	1	0	1	na	na	Axia Seeds (2022)

Pear	Vibranio	na	1	1	0	na	na	CapGen Seeds (2022)
Round	Agasi F1	na	1	1	na	1	na	
	Ronaldo F1	na	1	na	na	1	na	
	T-11641 F1	na	na	1	na	1	na	
Pear	Federer F1	na	na	1	na	1	na	
	Meyity F1	na	1	1	na	1	na	
	Nastase F1	na	1	1	na	1	na	Intersemillas (2022)
	Ramona F1	na	1	1	na	1	na	
	Royalty F1	na	na	1	na	1	na	
	Sampras F1	na	1	1	na	1	na	
	Patrol F1	na	1	na	na	1	na	
Marmande	T-11784 F3	na	1	na	na	na	na	
Round	Larguero	na	na	1	na	1	na	
Pear	Guillén	na	1	0	1	na	na	FiloSem (2022)
	Grandoly	na	1	0	1	na	na	
Round	Rosantea F1	na	1	0	1	na	na	
	Eracle F1	na	1	0	1	na	na	
Beef	Clizia F1	na	1	0	1	na	na	MedHermes (2022)
	Almanzor f1	na	1	0	1	na	na	
Pear	Ares F1	na	1	0	1	na	na	
Cocktail	Anahita F1	na	1	0	1	na	na	
Round	Tovi Total	na	1	0	1	1	na	
	Ganges	na	1	0	1	1	na	
Beef	Tovi Cala	na	1	0	1	na	na	Zeraim Ibérica Seeds(2022)
Pear	Papales	na	1	0	1	1	1(a)	
	Caniles F1	na	1	0	1	na	1(a)	
Cherry	Karelya	na	1	0	1	na	na	
Saladette	WranglerF1	0	na	na	na	na	na	HM Clause Seeds (2022)
	OutlanderF1	0	na	na	na	na	na	
Saladette	Canelo	0	0	0	1	na	1(a)	Hazera Seeds (2022)
Round	Fujimaru	na	na	0	1	na	1 (a)	
Cherry	SV0948TS	na	na	0	1	na	1 (a)	Bayer Seeds (2022)
Saladette	SV3543TE	na	na	0	1	na	1 (a)	
Grape	SVTJ7518	na	0	0	1	na	na	

Notes: * resistance traits: 0= intermediate resistance; 1= high resistance; na= not available or described

to determine a real value, but perhaps the economic impact of viral diseases in tomato is hovering around figures in bn US dollars. Even though there are no recent official statistics on economic losses due to tomato viruses, the main limitation is to extrapolate and accurately predict today's losses with data from the past decade. All this without considering the devaluation of the unit of measurement or the impact inflation has on the price and total value of the product.

We have delimited our review to current reports of viruses that infect tomato crops, considering the economic aspect and current state of the art; information that is scarce. Certainly, the main challenges for estimating the economic impact of viral diseases in tomato crops lie in the following reasons. First, the omission by growers about the presence of viral disease symptoms in their crops, coupled with the lack of official information by plant health authorities, makes it difficult to estimate a global picture of losses due to virus diseases. Second, the value of the product in the market differs according to the geographic area. Chanda et al., (2021) mentioned a point difference in terms of interest in tomato production. Florida state in the USA, has a focus on higher yields and useful life, regarding the production of export tomatoes in Mexico, more committed to increasing the quality of the texture and the flavor of the product. In this sense, different purposes of the same crop can have a different economic impact. Finally, is that, with the similarity in symptoms and signs that certain viruses present, it is difficult to know the causative agent. Today, rapid methods based on immunochromatography (immunostrips) for the detection of viral diseases present cross-reactivity with other viruses (Batuman et al., 2020), causing uncertainty and a poor level of differentiation of etiological agents. Finally, **Figure 1** establishes through a SWOT analysis the critical points of current tomato production in the world.

Conclusion

Tomato cultivation around the world has a positive impact on the generation of jobs and food security and is a fundamental pillar in the generation of GDP in producing countries. The main threats to tomato cultivation are viral diseases, among which ToBRFV, TSWV, and TYLCV are the agents with very few combat options, leading to the total loss of production if timely combat measures are not taken. Considering the absolute value of tomato cultivation around the world, economic losses due to viral diseases should be around 2 to 5% annually.

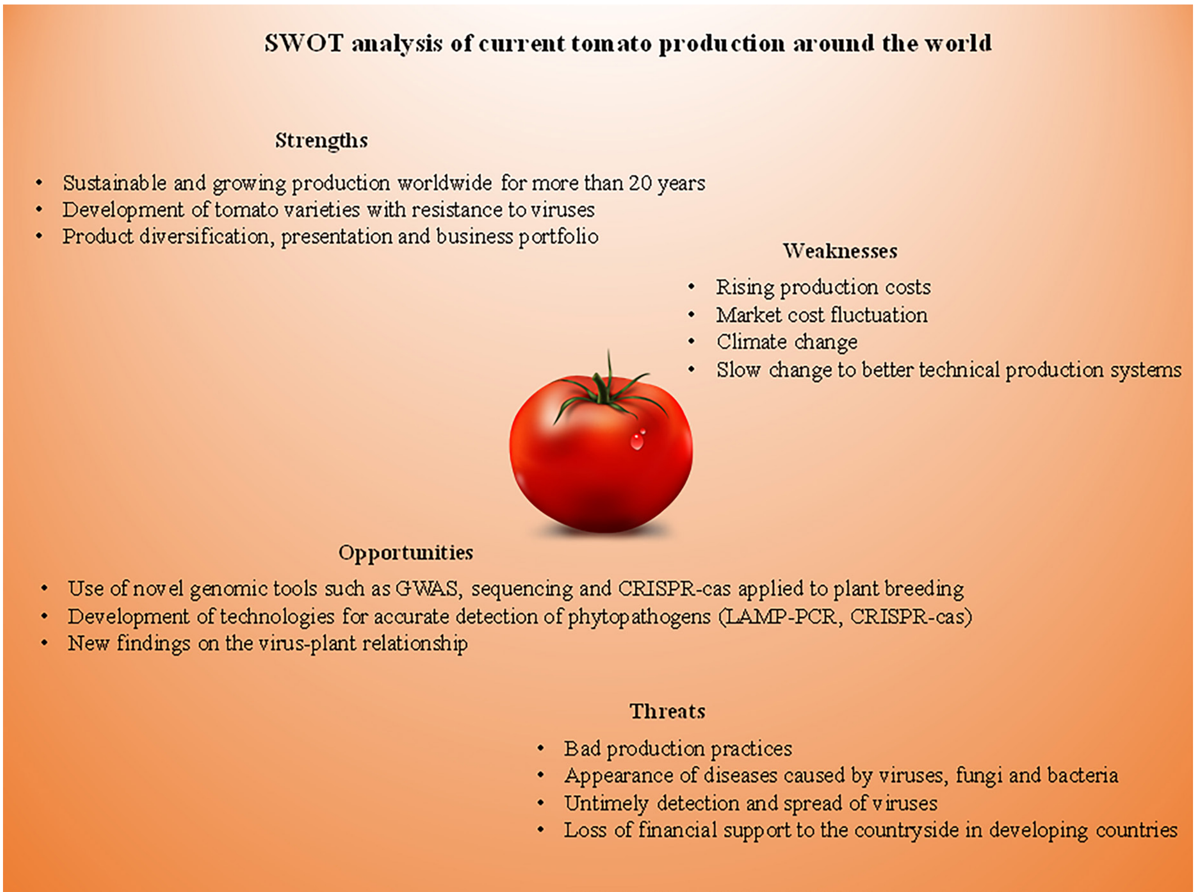

Figure 1. Current situation of the tomato crop, through SWOT analysis. Image credit @ Judy Murphy, available in: https://freepngimg.com/png/21751-tomato-vegetable-cartoon (CC BY-NC 4.0).

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