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Response diversity and traits related to pepper yellow leaf curl disease resilience for resistant plants selection

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Abstract. *Sayekti TWDA, Syukur M, Hidayat SH, Maharijaya A, Sobir. 2023. Response diversity and traits related to pepper yellow leaf curl disease resilience for resistant plants selection. Biodiversitas 24: 5057-5064.* Many chili species (*Capsicum* spp.) have been used and consumed, among them five species, namely *Capsicum annuum, C. frutescens, C. chinense, C. baccatum* and *C. pubescens*, are widely used. Most of these varieties are susceptible to Pepper Yellow Leaf Curl Disease (PYLCD) caused by Pepper yellow leaf curl virus (PYLCV) (*Begomovirus*, Geminiviridae). To control PYLCD, it is essential to gather resistant plant varieties to effectively shield cultivated plants from viral infections. An effective selection activity related to the target character is needed to get highly productive resistant plants. The objective of this study was to evaluate the relationship between resistance characters to crop production and to obtain appropriate selection criteria to increase the effectiveness of selecting resistant plants with good production. This study was conducted at Cikabayan Field, IPB University, Bogor, Indonesia. Twenty-nine genotypes of chili pepper were used, which consists of four species, including *C. annuum, C. frutescens, C. chinense,* and *C. baccatum,* arranged in a nested block design with three replications. The observed symptoms were yellowing of leaves followed by leaf malformations, but there were differences in the yellowing symptoms. From observation on visual symptoms, resistance characteristics, plant performance and productivity, there were differences in the response of each species to PYLCV attack. Correlation and path analysis results show that there was also differences in performance drop between *C. annuum* species and the non-*C. annuum* group. In *C. frutescens, C. chinense,* and *C. baccatum*, direct selection on resistance characters was able to increase the resistance level of selected plants while maintaining good crop production. Whereas for *C. annuum* species, the plant resistance level was not correlate with productivity reduction, so in the selection process, the percentage of yield decline needs to be considered to obtain resistant plants and maintain crop production.

Keywords: *Begomovirus, Capsicum*, high productivity, path analysis, PYLCV

INTRODUCTION

Chili pepper (*Capsicum* spp.) have become a significant horticultural commodity in Indonesia due to their high economic value and widespread utilization in various applications. Chili peppers are commonly used as a food and the main source of spiciness in Indonesia because they contain capsaicin. The capsaicin content in chili pepper is also widely utilized for bio-pharmaceutical purposes and antimicrobial agent (Bicikliski et al. 2017; Zhang et al. 2021). Furthermore, some types of chili pepper are also starting to be cultivated as ornamental plants (Virga et al. 2020). The significant utilization of chili pepper in various aspects is contributing to increasing demand for chili commodities, but until now, only five species have been widely used: *Capsicum annuum, C. Frutescens, C. Chinense, C. Baccatum* and *C. Pubescens.*

Chili pepper is susceptible to various plant diseases, including Pepper Yellow Leaf Curl Disease (PYLCD) (Srivastava et al. 2017). This disease is caused by Pepper yellow leaf curl virus (PYLCV) (*Begomovirus*, Geminiviridae). PYLCV transmission generally occurs through an insect vector, commonly in the form of whitefly (*Bemisia tabaci*). This virus has been widely reported to cause yield losses of up to 80%. PYLCV infection can be detected as thickening of the veins, leaf curls, yellowing and stunting (Lapidot et al. 2015). Control of PYLCV is still limited to controlling insect vectors, which are deemed ineffective in preventing the spread of PYLCV in the field. According to Barchenger et al. (2019) creating PYLCV-resistant plants is an effective way to control the spread of PYLCD in chili pepper.

To develop disease-resistant varieties, information is needed on the source of PYLCV resistances in chili plants. There have been many explorations and studies related to this resistance, not only limited to chili pepper but also to different commodities (Koeda et al. 2021; Koeda et al. 2022), such as tomatoes, beans, and cotton. On the other hand, this disease has received special attention in tomato plants, leading to extensive development of resistant varieties. Until now, a total of six loci that confer resistance against Begomovirus (Ty-1 to Ty-6) have been identified and cloned in tomato plants (Gill et al. 2019). On the other hand, the development related to PYLCD in chili plants still lags behind.

Even though chili pepper have been widely characterized and developed, only a few chili genotypes have resisted PYLCV until now. Resistance traits against *Begomovirus* have been reported in several accessions of *C. annuum* species, including 'PBC 495', 'IPBC12' (Ganefianti et al. 2015; Ayu et al. 2021) and 'Anies', as well as in *C. frutescens* such as 'Bonita' (Sayekti et al. 2021) and *C. chinense* species such as 'Bhut Jolokia' (Adluri et al. 2017). Despite having confirmed good resistance responses, the mechanisms of resistance and the genes responsible for conferring resistance traits in these accessions have not been identified.

Chili resistance to PYLCV is thought to be controlled by a resistance gene (R-gene), which generally has a gene-to-gene relationship, where each resistance gene effectively responds to a pathogen's specific pathotype (Soosaar et al. 2005). This causes the resistance mediated by the R-gene to be easily broken (Silva et al. 2014; Xavier et al. 2021). On the other hand, according to Liu et al. (2017), the presence of mutations in plant genes associated with viral infection can make an individual plant resistant. This mechanism is generally called recessive gene-mediated resistance. One example is the mechanism of the *pepy-1* gene reported by (Koeda et al. 2021), as it is a recessive gene, it is still difficult to develop resistance through this gene.

To get plants with good levels of resistance and high productivity, creating resistant plants is quite difficult. An effective selection activity related to the target character is needed to get highly productive resistant plants. Most of the selection for disease-resistant plants still focuses on the severity of the disease and symptoms experienced by individual plants. However, selecting for resistance traits only does not guarantee obtaining plants that have a good productivity.

The aim of this study was to evaluate the relationship between resistance characters to chili pepper production and obtaining appropriate selection criteria to increase the effectiveness of selecting resistant plants with good productivity.

MATERIALS AND METHODS

Study area and genetic material

This study was conducted at Cikabayan Field, IPB University, Dramaga Bogor, Indonesia (192 m asl). Plants were grown between the rainy season from August to December 2021.

Twenty-nine genotypes of chili pepper were planted in a greenhouse. Those genotypes consisted of four species, including *C. annuum, C. frutescens, C. chinense,* and *C. baccatum*, that has a various type of resistances to PYLCV. List of genetic material used is shown in Table 1. This experiment was arranged in Nested Block Design with twenty-nine genotypes which planted in two different conditions (virus-infected condition and virus-free condition (as control). The experiment was done with three technical replications and ten plants per unit for biological replication. Transmission of PYLCV was done using whitefly (*Bemisia tabaci*) as a vector.

The virus inoculum used was Pepper yellow leaf curl virus (PYLCV). The inoculum used in this study was identified and characterized through a DNA sequencing procedure according to the method of Ayu et al. (2021). The isolate has high homology with Pepper yellow leaf curl Indonesian virus and Pepper yellow leaf curl Indonesia Talibeng virus I (Ayu et al. 2021).

Procedures

Vector insects were obtained by exploring eggplant and chili plantations around IPB University. The insect vector, whitefly (*Bemisia tabaci*) obtained from exploration, was reared on a healthy cotton plant for two months until it became reproduced. The vector used was the second or third generation, so it was expected to be virus-free. The inoculum used was isolated Pepper yellow leaf curl virus from the collection of the Virology Laboratory, Department of Plant Protection, IPB University, Bogor, Indonesia.

Each genotype was sown and then transplanted into 20 cm pots. The growing media used was a mixture of soil, husk charcoal and cocopeat, with a ratio of 1:1:1. Inoculation was done 10 days after transplanting or when the plants had four leaves (4-leaf phase). Inoculation was carried out using the individual inoculation method proposed by (Gaswanto et al. 2016), with 24 hours of acquisition access period (AAP) and 48 hours of inoculation access period (IAP).

Table 1. Genetic material of 29 chili peppers

Genotypes	Species	Resilience
Yuni	*C. annuum*	Highly susceptible
IPBC12	*C. annuum*	Moderate resistant
IPBC15	*C. annuum*	Moderate resistant
Ungara	*C. annuum*	Moderate resistant
Anies	*C. annuum*	Resistant
Seloka	*C. annuum*	Moderate resistant
SSP	*C. annuum*	Susceptible
IPBC5	*C. annuum*	Susceptible
IPBC3	*C. annuum*	Resistant
F5-012328-6-2-1	*C. annuum*	Resistant
F5-012328-1AB-2-1	*C. annuum*	Resistant
F5-012328-6-2-2	*C. annuum*	Moderate resistant
F4-012328-1AB-3	*C. annuum*	Resistant
F4-012328-3-3	*C. annuum*	Moderate resistant
F6-074	*C. annuum*	Resistant
F1 Baja	*C. annuum*	Moderate resistant
Caman	*C. annuum*	Resistant
Adelina	*C. annuum*	Resistant
IPBC333	*C. frutescens*	Moderate susceptible
IPBC290	*C. frutescens*	Resistant
Bonita	*C. frutescens*	Moderate resistant
Taruna	*C. frutescens*	Moderate susceptible
Cakra Putih	*C. frutescens*	Moderate resistant
Red Habanero	*C. chinense*	Resistant
Jolokia	*C. chinense*	Resistant
Fatali	*C. chinense*	Resistant
Red Chupetinho	*C. chinense*	Resistant
Bishop Crown	*C. baccatum*	Susceptible
Lemon Drop	*C. baccatum*	Highly susceptible

Source: Sayekti et al. (2021)

Observations were made on the morphological and agronomic traits in both growing environments. Observations included characteristics of leaves, stems, and fruit. Additionally, observations were also made on the plant resistance characteristics, namely the disease's incubation period, incidence rate, and severity. Plants were observed from inoculation up to 30 days after inoculation (DAI). Visual symptoms were observed in the tissues of inoculated plants. The observed symptoms were then classified using the disease severity scale modification from Barchenger et al. (2019) and Dai et al. (2022). Score 0 corresponds for healthy plant with no symptoms; 1 for yellowing symptoms; 2 for yellowing and curling symptoms; 3 for yellowing, curling, and cupping symptoms; and 4 for yellowing, curling, cupping and stunting symptoms.

This score was used to determine the level of plant resistance to PYLCV using the following formula:

$$DSI = [(sum\ (n_i \times z_i)) / (N \times Z)] \times 100\%$$

Where, DSI: disease severity Index; ni: class frequency; zi: assessment class score; N: number of plants observed; Z: maximum disease index.

Data analysis

Quantitative data was analyzed using F-test for analysis of variance followed by Duncan Multiple Range Test (DMRT). These analyses were performed using SAS 9.4 software. Data was also analyzed using Pearson correlation and path analysis performed using Minitab-16 software.

RESULTS AND DISCUSSION

Evaluation of disease symptoms

The incubation period, disease incidence and severity were observed based on the visual symptoms. The results of observations on visual symptoms showed that there were differences in the symptoms of PYLCV infection in each chili species. In general, the observed symptoms were yellowing of leaves followed by leaf malformations, but there were differences in yellow spots that were observed. In *C. annuum*, symptoms begin to appear from the young leaves (plant shoots) and then gradually spread to other parts of the plant leaves; blanching of the veins occurs, and the symptoms begin to spread from the base to the tip of the leaf (Figure 1a). Advanced symptoms include leaf malformations, curly and curved leaves (cupping), and stunted plants. Symptoms of PYLCV infection in *C. baccatum* species were yellowing of leaves followed by malformations and curling of young leaves (Figure 1b). The yellowed part was the part of the leaf between the veins, while the veins were still green. Later, due to symptoms of severe infections, the plant showed stunted growth and there was significant loss of flowers.

Different symptom patterns were observed in the genotypes derived from *C. frutescens*. The yellow spots did not start from young leaves but appeared randomly on all parts of the plant leaves. The yellow spots were uneven, so it looked as if they were forming a mosaic pattern (Figure 1c). Rolling and thickening of leaves were also observed. In this study, no symptoms of stunting were observed in *C. frutescens*. The observed symptoms of the genotypes derived from *C. chinense* were yellow spots that appeared randomly on the leaf surface (Figure 1d). There was no thickening of leaves and they were slightly curled but not rolled. Symptoms were not always appeared and start from young leaves. It is believed that differences in symptoms and plant resistance levels were influenced by differences in plant defense mechanisms against PYLCV infection. Plants generally have developed mechanisms of resistance to viral attack or infection. The first mechanism is plant resistance mediated by resistance genes (R-gene) and the second mechanism is RNA-silencing (Chen et al. 2018; Ashfaq et al. 2020). A resistance gene (R-gene) generally confers specific resistance to certain pathogens, including viruses. In this mechanism, most of the resistance responses shown are hypersensitive responses (HR), in which the plant activates the death of cells around the infected area (Programmed Cell Death/PCD) (Soosaar et al. 2018). This mechanism leads to symptoms such as random chlorosis or necrosis spots on the leaves. These spots usually form around the area where the virus is transmitted.

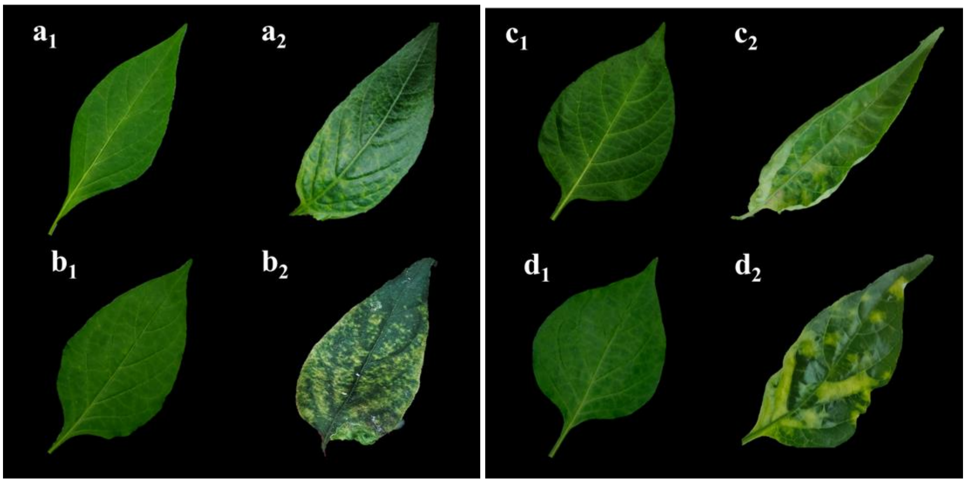

Figure 1. The difference between healthy (1) and symptomatic (2) leaves in four different species of chili peppers. a. *C. annuum*; b. *C. baccatum*; c. *C. frutescens*; d. *C. chinense*

Reduction in plant size

In this study, there were nine quantitative characters and three resistance characters tested. Analysis of variance (ANOVA) showed that all recorded quantitative traits were significantly differed among species (Table 2). The same thing was observed in the growing environment treatment. All recorded traits also differed among growth conditions except stem diameter. The coefficient of variation ranged between 1.71-4.95%. All the observed characters had a wide range. This may be because a variety of chilies from different species with different plant and fruit characteristics were used in this experiment.

The analysis of variance also indicates interactions between species and growing environment that influence all observed traits except stem diameter. This indicates differences in response patterns among each genotype to PYLCV-infected conditions. In general, test plants showed a reduction in size under PYLCV infection conditions, but some genotypes did not show a response to dwarfism (plant size reduction).

Differences in plant response to PYLCV infection were observed among different chili species. Chili genotypes derived from *C. annuum* species were observed to experience reductions in leaf length, leaf width, and plant height. A different phenomenon was observed in the genotypes derived from *C. frutescens*, *C. chinense*, and *C. baccatum*. In these three species, only leaf size was reduced, but plants tended to be higher in virus-infected conditions than in virus-free conditions (Table 3). The reduction in leaf width ranged from 1.61%-10.96%, and reduction in leaf length ranged between 10.20%-25.13%.

Genotypes derived from the species *C. baccatum* showed a reduction in leaf length, but did not experience leaf width, stem diameter, and plant height reduction. This phenomenon indicates differences in resistance levels and mechanisms of resistance to PYLCV attack among chili species.

Leaf size, stem and plant height were observed after the plants entered the harvest period. The leaves observed were those on the main branching according to the guidelines published by IPGRI et al. (1995). Plant size reduction can occur in chili infected with PYLCV due to PYLCD symptoms. Symptoms of PYLCD, include chlorosis, cupping, curling, stunted plants, and flower loss (Khalil et al. 2020).

Observations were also made on fruit characters and plant productivity in virus-free and virus-infected conditions. Plants infected with the virus had smaller fruit sizes and fewer fruits than virus-free conditions (Table 4). This phenomenon was observed in all the species tested. The decrease in fruit size in *C. baccatum* species was the greatest compared to other test species.

Table 2. Analysis of variance of several traits in chili pepper under two different growth conditions

Characters	Ranges	Mean square			CV (%)
		Species	Growth conditions	Species x growth conditions	
Leaf length (cm)	7.02-16.66	10.521**	18.480**	0.406**	1.71
Leaf width (cm)	2.84-9.44	19.739**	1.848**	0.187**	1.87
Stem diameter (cm)	0.52-0.88	0.033**	0.003tn	0.000tn	3.30
Plant height (cm)	43.58-116.63	2272.582**	279.893**	140.295**	1.81
Fruit length (cm)	1.98-16.03	34.109**	2.700**	0.549**	2.65
Fruit diameter (cm)	0.39-4.11	4.407**	0.123**	0.044*	4.11
Fruit weight (g)	1.02-17.85	38.293**	2.620**	1.399**	2.47
Number of fruit per plant	3.40-55.53	510.185**	43.121**	43.719**	6.32
Yield per plant (g)	24.09-133.64	512.110**	192.553**	79.820**	4.95

Note: CV: coefficient of variance; *significant at level of 5%; **significant at level of 1%; ns: not significant

Table 3. Morphological traits of four species chili pepper in different growth conditions

Species	Leaf width (cm)		Leaf length (cm)		Stem diameter (cm)		Plant height (cm)	
	Non-virus	Virus	Non-virus	Virus	Non-virus	Virus	Non-virus	Virus
C. annuum	4.85 d	4.43 e	12.25 e	10.70 f	0.67 de	0.67 e	72.77 e	68.25 f
C. frutescens	8.18 b	7.48 c	15.49 a	12.95 d	0.83 ab	0.82 ab	102.33 c	115.17 a
C. chinense	8.67 a	7.72 c	15.09 a	13.55 c	0.84 a	0.80 b	91.49 d	108.11 b
C. baccatum	8.68 a	8.54 a	17.19 b	12.87 d	0.74 c	0.72 cd	70.65 ef	73.04 e

Note: Number followed by the same letter in the same line and column were not significantly different to DMRT 5% level

Table 4. Fruit characteristics of chili pepper in different growth conditions

Species	Fruit length (cm)		Fruit diameter (cm)		Fruit weight (g)		Number of fruit		Yield per plant (g)	
	Non-virus	Virus	Non-virus	Virus	Non-virus	Virus	Non-virus	Virus	Non-virus	Virus
C. annuum	8.79 a	7.92 b	1.89 d	1.80 d	8.21 a	6.54 b	18.19 c	8.21 e	105.29 a	37.14 d
C. frutescens	3.62 d	3.59 d	1.01 e	1.04 e	1.25 f	1.37 f	63.04 a	21.31 b	70.02 b	28.44 de
C. chinense	3.91 c	3.56 d	2.89 ab	2.75 bc	4.76 e	4.97 d	22.80 b	13.83 d	57.45 c	31.32 de
C. baccatum	4.15 c	2.73 e	2.98 a	2.61 c	6.02 c	4.72 e	13.00 d	4.11 f	54.77 c	23.67 f

Note: Number followed by the same letter in the same line and column were not significantly different to DMRT 5% level

Chili plants infected with PYLCV produced less fruit than those grown under virus-free conditions. The highest reduction in the number of fruits was observed in *C. baccatum*, which reached 68.38% (from 13.00 to 4.11 fruits per plant). The reduction in the number of fruits due to PYLCV infection was also followed by a decrease in yield per plant. The highest reduction in yield per plant was observed in *C. annuum*, which reached 64.72% (from 105.29 g to 37.14 g). Plant response to virus attacks can vary among plant species. According to Rai et al. (2014), one of the symptoms of PYLCD attack is the loss of flowers and fruit, resulting in significant yield loss. It has been reported that yield losses due to PYLCD attacks have reached up to 80%, making it detrimental for farmers. In addition, disturbed plant growth can reduce fruit formation, size, and discoloration (in certain species) (Dombrovsky et al. 2010) and also can cause a decrease in fruit quality. In this case, gathering resistant plants is necessary to consider the productivity and quality of the fruit produced.

Selection criteria for resistant plants

Selection of disease-resistant plants was generally done by focusing on the level of symptoms development. *Begomovirus* attack symptoms appear and are observed in plants when virus accumulation in plant tissues reaches a maximum limit of 3.8 to 4.4 ng/µg plant DNA (Ber et al. 1990; Simón et al. 2018). In this case, the visual symptoms observed in plants can represent the level of plant resistance to speed of virus replication in the tissue. On the other hand, under conditions of virus infection, plants tend to experience a decrease in performance as the severity of disease increases (Sayekti et al. 2021).

This study conducted correlation and path analysis to find information on each character's direct and indirect effects, which can be used as a selection criterion for resistant plants with good production. Correlation analysis is a method to understand the connection between multiple quantitative variables. A widely used approach is the Pearson correlation, especially when dealing with variables measured on an interval or ratio scale. A linear relation between the two variables is represented by the correlation coefficient (r) between -1 and 1 (Wright 1921).

The results of analysis showed that disease severity, disease incidence, incubation periods (IP), reduction of plant height (PH), fruit diameter (FD), number of fruit (NF), and fruit weight (FW) had a significant correlation with yield per plant reduction. The correlation coefficient values between these characters were 0.349, 0.299, -0.277, 0.338, 0.224, 0.839, and 0.308, respectively. Although it can explain the relationship between characters, correlation analysis cannot explain the impact of a secondary trait on the main trait. To understand the relationship between these causal and effect factors better, path analysis is employed.

Path analysis offers a useful approach for dissecting the direct and indirect factors influencing relationships. Regarding crop yield, various factors come into play, and relying solely on correlation might lead to misleading conclusions since it only assesses the mutual association between two characters (Izge et al. 2012).

The results show that percentage reduction in number of fruit (0.903) and fruit weight (0.457) had a large positive direct effect on decreasing yield per plant (YPP) (Figure 2). This suggests that directly focusing on these traits could be an effective strategy for selection, potentially leading to an improvement in yield per plant through their targeted enhancement (Kumar et al. 2013; Lestari et al. 2023). The other observed characters tend to have a low direct effect on the yield per plant reduction.

Although the direct effect was small, disease severity had a positive indirect effect (0.250) on yield per plant reduction through decreasing the number of fruit (Table 5). Focusing on these results, selection can be made using disease severity characters to obtain resistant plants with good productivity. The path analysis conducted in this study had a low residual value, which was 0.088. Low residual value of path analysis indicate that maximum trait that contributing to decreasing plant yield were considered in the present study (Chakrabarty and Islam 2017).

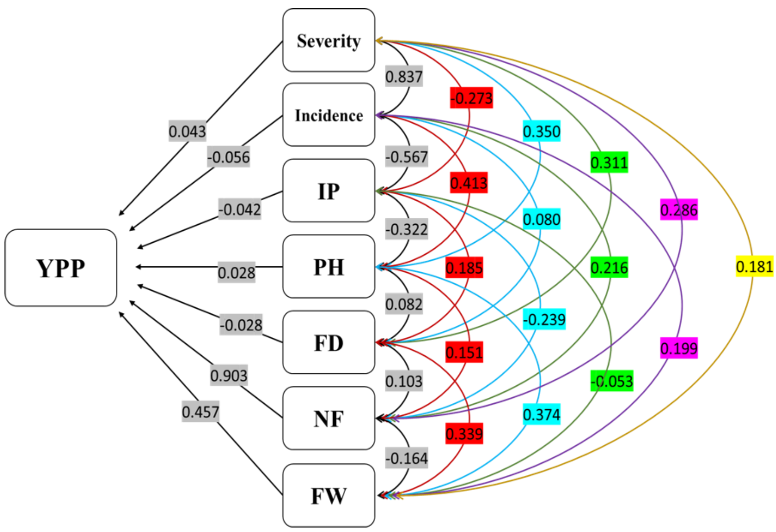

Figure 2. Diagram of the direct effect and correlation between plant size reduction and disease severity. Note: Severity: disease severity; Incidence: disease incidence; IP: incubation periods; PH: reduction of plant height; FD: reduction of fruit diameter; NF: reduction on number of fruits; FW: reduction of fruit weight; YPP: reduction of yield per plant

Table 5. Direct and indirect effects for reduction of yield per plant chili pepper

Characters	Direct effect	Indirect effect							rXY
		Severity	Incidence	IP	Plant size reduction				
					PH	FD	NF	FW	
Severity	0.043		0.292	-0.095	0.122	0.109	0.100	0.063	0.349
Incidence	-0.056	0.250		-0.170	0.123	0.024	0.065	0.060	0.299
IP	-0.042	0.076	0.157		0.089	-0.051	0.066	0.015	-0.277
PH	0.028	0.118	0.140	-0.109		0.028	0.051	0.126	0.338
FD	-0.028	0.070	0.018	0.041	0.018		0.023	0.076	0.224
NF	0.903	0.240	0.181	-0.201	0.127	0.086		-0.138	0.839
FW	0.457	0.056	0.061	-0.016	0.115	0.104	-0.051		0.308
Residual	0.088								

Note: Severity: disease severity; Incidence: disease incidence; IP: incubation period; PH: plant height; FD: fruit diameter; NF: number of fruit per plant; FW: fruit weight

Table 6. Coefficient of correlation between characters in different chili species

Severity	Incidence	Percentage of plant size reduction									
		IP	LL	LW	SD	PH	FL	FD	NF	FW	YPP
C. annuum	0.873**	-0.344	0.460**	0.396**	0.094	0.422**	-0.011	-0.120	0.058	-0.047	0.118
Non-*C. Annuum*	0.919**	-0.766**	0.132	0.110	-0.050	0.335	-0.257	-0.358	0.526**	-0.092	0.527**

Note: **significant at level of 1% Pearson correlation

The selection of secondary characters requires several considerations, including the correlation between characters, direct and indirect effects, and the heritability of related characters. Several reports show that the resilience characters, namely disease severity, and incidence, have large heritability ranging from 51.26% (Hafsah et al. 2023) to 65.16% (Sayekti et al. 2021). The high heritability value, a positive correlation between characters, and an indirect effect can make the disease severity character a secondary selection character.

Observations on leaf, stem, fruit, and productivity showed that, under PYLCV-infected conditions, plants could experience a decrease in vegetative characteristics without decreasing production, but vice versa. These differences in response must be considered in determining selection criteria to obtain disease-resistant plants with good productivity.

To obtain suitable selection characters for each species, this study conducted a correlation analysis between the percentage reduction in plant performance and yield with plant resistance level. The analysis was carried out separately on two major groups: *C. annuum* species group and the non-*C. annuum* species group. The results showed different patterns between the two groups (Table 6). Analysis of genotypes derived from *C. annuum* species showed that plants tended to experience damage and decreased vegetative characteristics such as leaf size and stem size but had no significant correlation with the rate of fruit characters and productivity reduction.

A different phenomenon was observed in the non-*C. annuum* group (*C. frutescens*, *C. chinense*, *C. baccatum*). The analysis carried out in this group showed a correlation between disease severity and the number of fruits reduction and yield per plant, but not for other characters. Many reports have also revealed that chili pepper from *C.* chinense (García-Neria and Rivera-Bustamante 2011), *C. frutescens*, and *C. baccatum* (Parisi et al. 2020), tend not to experience plant damage and have mild symptoms, but experience fruits and productivity reduction, which increases with increasing disease severity. In the species *C. frutescens*, *C. chinense,* and *C. baccatum*, the percentage of decline in plant productivity can be predicted through the disease severity index.

On the other hand, chilies from the species *C. annuum* tend to experience severe symptoms of plant damage and malformation as the disease's severity increases. Fruit size and quantity were generally not correlated with disease severity. Since there is no correlation between disease severity and the percentage of reduced fruit characters in *C. annuum*, disease severity alone does not indicate reduced plant productivity. Plants certainly experience a decrease in production when subjected to stress, whether biotic or abiotic. The same applies to Begomovirus attacks, which have been widely reported to cause yield losses in chili peppers (Kesumawati et al. 2018) and other host plants such as long beans (Dhobale et al. 2023), tomatoes and okra (Leke et al. 2015). In this case, the percentage of fruit character and productivity reduction cannot be predicted using the disease severity index. Hence, it needs to be considered in the selection of resistant plants.

In summary, based on observations of visual symptoms, resistance characteristics, and dropped plant performance and productivity, there were differences in the response of each species to the PYLCV attack. This difference may be due to occur due to different resistance mechanisms. Correlation and path analysis results show that there was also a difference in performance drop between *C. annuum* species and the non-*C. annuum* group. Considering these results, it can be concluded that to obtain resistant plants with good productivity, it is necessary to consider other selection criteria than resistance, such as disease severity index.

It is new to find that for *C. frutescens*, *C. chinense*, and *C. baccatum*, direct selection on resistance characters is able to increase the resistance level of selected plants while maintaining good crop production. Whereas for *C. annuum* species, the level of plant resistance is not correlate with productivity reduction, so in the selection process, the percentage of yield decline needs to be considered to obtain resistant plants and maintain crop production.

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