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A comprehensive screening of sources of resistance in common bean genotypes to *Zabrotes subfasciatus* (Coleoptera: Chrysomelidae: Bruchinae)

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Abstract
The initial step in the successful implementation of a breeding program aimed at obtaining bruchid resistant beans lines is the identification of sources of resistance within a diverse germplasm. Here, a total of ninety two (92) Brazilian common bean genotypes were screened to identify promising sources of resistance to *Zabrotes subfasciatus* (Boheman) (Coleoptera: Chrysomelidae: Bruchinae), the primary insect pest of stored beans. The cultivars BRS Ametista and BRS Esplendor, as well as the bean lineages CHP 01-182-12-Uirapuru × Campeiro and CHP 04-241A-212-Guapo B. × Uirapuru exhibited the lowest oviposition rates. The genotypes BRS Ametista, CHP 01-182-12-Uirapuru × Campeiro and BRS Esplendor also showed the lowest average of adult emergence evidenced by the F_1 progeny. In contrast, genotypes BRS Ametista, CHP 05-282-04-Campeiro × Agudo, TB-17-02, CHC 01-167-1-03, IPR Uirapuru, CHIR 14, IPR Campos Gerais, CHIC 61-Cariocão, IAC Imperador, Arcelin 1, FAP-F3-2-SEL-IAC, CAV 17 EFM008, SCS 205-Riqueza, LP 13-634-preto, IAC Harmonia and Linhagem 110-IAC exhibited the lowest percentage of larval-pupal viability. Conversely, genotypes Arcelin 3, Arcelin 1, CHIN 19, CHV 05-268-02, LP 13-84-Carioca, CNFRs-15558-Rosinha, IPR Campos Gerais, CHC 01-175-1-Campeiro × IAC Tibatã, BRS Notável, IPR Uirapuru, BRS Estilo, IPR Quero-Quero, CAV 17 EFM0006, CHP 04-241A-212-Guapo B. × Uirapuru, BRS Esplendor, and CHP 01-182-12-Uirapuru × Campeiro were observed to significantly prolong the developmental time (cycle) of *Z. subfasciatus*, indicating the expression of antixenosis and/or antibiosis type resistance. Thus, these genotypes are promising sources of resistance to *Z. subfasciatus*, and further studies are recommended to elucidate the underlying mechanisms and genes involved.

Keywords *Phaseolus vulgaris* · Mexican bean weevil · Antixenosis · Antibiosis

1 Introduction

In the context of agricultural storage in tropical environments, both the high pressure of insect pests and the occurrence of resistant populations to the main active ingredients used in warehouses [40] as well as the ecotoxicological risks of xenobiotics in foodstuffs have prompted the search for alternative strategies [22]. The most effective method

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of addressing these challenges in an environmentally sustainable way is through the breeding of crops with enhanced resistance to storage insect pests [1, 25, 27].

In response to a race driven by the evolutionary dynamics of insect-plant interactions, a diverse array of physical, chemical, and morphological defense strategies was selected to safeguard the plant and its progeny (i.e., seeds) from herbivory, encompassing different signaling pathways [8, 52]. This line of defense occurs through constitutive and genetically inherited characteristics that make a cultivar or species more resistant to damage caused by associated herbivores [7, 39, 48].

From an applied perspective, the identification of both sources of resistance and genes that encode these mechanisms as well as methods of incorporating these characteristics into cultivars to express resistance to biotic stresses has the potential to transform the pest management scenario in agricultural systems [7]. Nevertheless, the initial step towards the success of this process is the identification of sources of resistance within a diverse germplasm [12]. In general, resistance involves a combination of morphological, physiological, and biochemical factors, including morphological barriers, secondary metabolites, and anti-nutritional compounds [19]. For example, in wild species of *Phaseolus*, arcelin, phytohemagglutinin, α-amylase inhibitor, and anti-nutritional proteins collectively called lectins were identified, cloned, sequenced, and deployed in breeding programs [2, 19, 27].

The common bean [*Phaseolus vulgaris* L. (Fabaceae)] is a staple food in many regions of the world and, consequently, a key component of food security in undeveloped and underdeveloped countries located, particularly in Africa and South America [15]. However, the infestation of the Mexican bean weevil [*Zabrotes subfasciatus* (Boheman) (Coleoptera: Chrysomelidae: Bruchinae)] has been identified as a significant threat to stored beans in tropical and subtropical regions, with estimated losses reaching 13% [25, 44]. Consequently, this pest is regarded as a major concern for the agricultural production of the legume. The damage caused by this pest is the result of the penetration of larvae into the grains, leading to the loss of mass and a reduction in nutritional value. Additionally, there is a loss in product quality due to the presence of eggs, excrement and larvae in the grain mass [26]. Indirect damage is associated with the presence of mycotoxin fungi, spoilage fungi species, and mites, which are facilitated due to the holes left by adults when they leave the grains [20, 44]. In addition to quantitative losses, the damage caused by *Z. subfasciatus* renders the consumption and industrial processing of the affected beans unfeasible [38].

A number of studies have been conducted with different common bean genotypes, which have demonstrated a range of levels of antibiosis and/or antixenosis type resistances against *Z. subfasciatus* [6, 10, 25, 35]. Nevertheless, despite the considerable research efforts that have been undertaken, the levels of resistance that have been identified in commercial cultivars remain relatively limited, thereby providing a rationale for future research with a broader range of germplasms.

Given the considerable losses of stored bean grains resulting from infestation by the bean weevil and the necessity of developing resistant commercial cultivars for integration into stored grain integrated management programs (IPM), the present study aimed to characterize the potential expression of resistance in ninety two (92) genotypes of *P. vulgaris* from diverse origins and characteristics with respect to *Z. subfasciatus*. The results of this comprehensive screening will contribute to the identification of potential sources of resistance for incorporation into breeding programs, as well as the selection of the most suitable genotypes or lineages for cultivation, particularly by small farmers or domestic producers in undeveloped or developing countries, where food security has been a significant concern.

2 Materials and methods

2.1 Insects

The Mexican bean weevils (*Z. subfasciatus*) utilized in the bioassays were obtained from a stock rearing established with insects collected in warehouses in the region of Chapecó, Santa Catarina State, Brazil. For the purposes of colony maintenance, clear glass flasks (10 cm height × 20 cm diameter) were utilized, closed at the top with organdy fabric, thereby facilitating internal aeration. Each flask was filled with 300 g of common bean grains (cv. Bolinha) and approximately 300 unsexed adult insects and maintained in a BOD-type chamber (25 ± 2 °C, RH = 70 ± 10%, and a photoperiod of 12 L:12 D h). The grains in the flasks were subjected to a 30-day sieving process, after which the newly emerged adults were utilized for infestation of new flasks or incorporation into the proposed bioassays.

2.2 Common bean genotypes tested

The genotypes studied were obtained from the germplasm banks of the Agronomic Institute of Campinas (IAC) and the Agricultural Research and Rural Extension Company of Santa Catarina (CEPAF/EPAGRI). Table 1 provides a detailed account of the respective genealogies, origins, and supplementary information for each genotype. In all bioassays, the IAC Una genotype was included as a susceptible standard, selected according to previous published manuscripts [18, 24].

2.3 Bioassays

In the initial phase of the study, a total of 92 common bean genotypes (Table 1) were evaluated to identify the most promising sources of resistance against the bruchid *Z. subfasciatus*. This was achieved thought the implementation of a no-choice bioassay, conducted under a completely randomized design.

For this purpose, 5 g of bean grains from each genotype were placed in transparent acrylic containers of 50 mL with lids (5 cm height × 3 cm diameter), which served as the experimental units. Subsequently, seven pairs of adult weevils (aged < 24 h) were introduced to each experimental unit for a 7-day period, with the objective of ovipositing on the grains. A total of 368 bottles (experimental units) were utilized, with four repetitions for each genotype. These bottles were maintained in a BOD-type chamber (27 ± 2 °C, RH = 70 ± 10%, and a photoperiod of 12 L: 12 D h).

After a period of 7 days in which the insects were allowed to infest the grains in the bottles, the insects were removed using tweezers and a sieve. In addition, on the twenty-first day post-infestation, the total number of eggs, as well as the number of viable and non-viable eggs, was counted in all experimental units using a stereoscopic microscope, as proposed by Mazzoneto and Vendramim [35]. Viable eggs had a larval exit hole, while non-viable eggs were intact with a hyaline coloration aspect [46]. Subsequently, the larval/pupal viability of the weevil was determined in the different bean genotypes.

At the 28th day after infestation (28 DAI), all 368 experimental units containing the different bean genotypes were sieved daily until no adults emerged for five consecutive days. The bean weevil cycle (developmental time) was then determined in each genotype using the following formula:

$$\sum xf/\sum x,$$

where: x: the number of adults emerging in that day; f: the number of emergence days [17].

2.4 Data analysis

For the data analysis, the normality of the residues with the Shapiro-Wilk test [51] and the homogeneity of variances with the Bartlett test [9] were first verified. When these assumptions were not found, the data were transformed using the optimal power method of Box and Cox [11]. Once the necessary assumptions were satisfied, the data were submitted to the analysis of variance, and the means for genotypes were compared using the Scott-Knott test [50] at $p < 0.05$.

A multivariate cluster analysis was conducted to validate the grouping of the genotypes under investigation, employing the following variables: larval-pupal viability (%), number of emerged adults, developmental time (cycle), and total number of eggs. The mean Euclidean distance, as a measure of dissimilarity, and the average distance method, as a clustering strategy, were employed because they exhibited the highest co-optic correlation [33]. The cut-off point was determined by considering half of the maximum adjusted Euclidean distance [21]. All statistical analyses were conducted using the R environment [45].

3 Results

Significant variation in oviposition of *Z. subfasciatus* was observed according to tested bean genotype (Table 2). The cultivars BRS Ametista and BRS Esplendor, as well as the bean lineages CHP 01–182-12-Uirapuru × Campeiro and CHP 04-241 A-212-Guapo B. × Uirapuru exhibited the lowest oviposition rates (between 41.50 and 81.75 eggs/sample)

Table 1 Origin and characteristics of common bean (*Phaseolus vulgaris* L., Fabaceae) genotypes tested for resistance to *Zabrotes subfasciatus* (Coleoptera: Chrysomelidae: Bruchinae)

No.	Genotype	Germplasm bank	Genealogy/origin/characteristics	Resistance history
1	CHP 01–182-12-Uirapuru × Campeiro	EPAGRI	Lineage obtained from the cross between 'IPR Uirapuru' and 'BRS Campeiro'	ne[a]
2	SM 0511-cavalo preto	EPAGRI	Not available	ne[a]
3	SM 1510-preto	EPAGRI	Not available	ne[a]
4	LP 13–624-preto	EPAGRI	Not available	ne[a]
5	TB-17-02	EPAGRI	Not available	ne[a]
6	TB-17-03	EPAGRI	Not available	ne[a]
7	CHP 01–182-48-Uirapuru × Campeiro	EPAGRI	Lineage obtained from the cross between 'IPR Uirapuru' and 'BRS Campeiro'	ne[a]
8	CHP 01–238-80-MN 13337	EPAGRI	Not available	ne[a]
9	CHP 04-241 A-212-Guapo B. × Uirapuru	EPAGRI	Lineage obtained from the cross between 'Guapo B.' and 'Uirapuru'	ne[a]
10	CHP 05–282-04-Campeiro × Agudo	EPAGRI	Lineage obtained from the cross between 'BRS Campeiro' and 'Agudo'	ne[a]
11	IPR Campos Gerais	EPAGRI	Not available	ne[a]
12	LP 13–84-Carioca	EPAGRI	Not available	ne[a]
13	Linhagem 110-IAC	EPAGRI	Not available	ne[a]
14	FAP-F3-2 Sel.-IAC	EPAGRI	Not available	ne[a]
15	LEC 04–16	EPAGRI	Not available	ne[a]
16	UEM 266	EPAGRI	Not available	ne[a]
17	CNFRs-15,558-rosinha	EPAGRI	Not available	ne[a]
18	CNFRj-15411-rajado	EPAGRI	Not available	ne[a]
19	CHC 01–175-1-Campeiro × IAC Tibatã	EPAGRI	Lineage obtained from the cross between 'BRS Campeiro' and 'IAC Tibatã'	ne[a]
20	CHC 04–233-2-Siriri × Horizonte	EPAGRI	Lineage obtained from the cross between 'Siriri' and 'Horizonte'	ne[a]
21	CHIC 61-Cariocão	EPAGRI	Access from the Epagri germplasm bank ('Cariocão'), collected in Campos Novos, SC (1997)	ne[a]
22	BRS Radiante	EPAGRI	Cultivar obtained from the biparental crossing between 'Pompadour' and 'Iraí'	ne[a]
23	CHIR 04	EPAGRI	Access from the Epagri germplasm bank ('Crioulo'), collected in Campos Novos, SC (1998)	ne[a]
24	CHIR 13	EPAGRI	Access from the Epagri germplasm bank ('Iraí'), collected in Campos Novos, SC (1998)	ne[a]
25	CHIR 14	EPAGRI	Access to the Epagri germplasm bank	ne[a]
26	CHC 01–167-1–03	EPAGRI	Not available	ne[a]
27	IPR Garça	EPAGRI	Not available	ne[a]
28	CHIB 06	EPAGRI	Lineage obtained from the cross between 'Ouro Branco' and 'Iraí'	ne[a]
29	CHIB 07	EPAGRI	CIAT lineage (EMP 194)	ne[a]
30	CHIB 11	EPAGRI	CIAT lineage (ABA-19)	ne[a]
31	CHIB 18	EPAGRI	Lineage obtained from the cross between CH 05–263-'Iraí' and 'Ouro Branco'	ne[a]
32	CHB 15–518	EPAGRI	Lineage obtained from the cross between CHIB 10 and CHIB 18	ne[a]

Table 1 (continued)

No.	Genotype	Germplasm bank	Genealogy/origin/characteristics	Resistance history
33	CHB 15–519	EPAGRI	Lineage obtained from the cross between CHIB 10 and CHIB 47	ne[a]
34	CHV 05–268-02	EPAGRI	Lineage obtained from the cross between 'Amendoim Cavalo' and G2333	ne[a]
35	CHV 17–635	EPAGRI	Lineage obtained from the cross between CHIV 57 and CHIV 76-F3	ne[a]
36	CHV 17–641	EPAGRI	Lineage obtained from the cross between CHIV 69 and CHIV 76-F3	ne[a]
37	Avaluna	EPAGRI	Not available	ne[a]
38	BRS Campeiro	EPAGRI	Cultivar obtained by induction of mutation aiming to change the color of the seed coat of the cultivar 'Corrente'	ne[a]
39	BRS Esplendor	EPAGRI	Cultivar obtained from the cross between 'CB911863' and 'AN9123293'	ne[a]
40	BRS Esteio	EPAGRI	Cultivar obtained from the cross between 'FT85-113' and 'POT51'	ne[a]
41	IPR Tuiuiu	EPAGRI	Not available	ne[a]
42	IPR Uirapuru	EPAGRI	Cultivar obtained from the cross between BAC29/PR1711/3/NEP2/2/Puebla 173/Icapijao	ne[a]
43	SCS 204-Predileto	EPAGRI	Selected from the MN 13337 population introduced into CIAT	ne[a]
44	SCS 206-Potência	EPAGRI	Not available	ne[a]
45	BRS Ametista	EPAGRI	Cultivar obtained from hybridization of lines PR99115957 and LR72098 CP	ne[a]
46	BRS Estilo	EPAGRI	Cultivar obtained from the cross between EMP 250/4/A 769///A 429/XAN 252//V 8025/PINTO VI 114, carried out in 1991 at CIAT	ne[a]
47	BRS Notável	EPAGRI	Cultivar obtained from crossing lines A769/4/A774///A429/XAN 252//V 8025/G 4449///WAF 2/A 55//GN 31/XAN 170	ne[a]
48	IAC Imperador	EPAGRI	Cultivar obtained from the cross between 'IAC Carioca Eté' × 'Carioca Precoce'	ne[a]
49	IPR Quero-Quero	EPAGRI	Not available	ne[a]
50	IPR Tangará	EPAGRI	Cultivar obtained from the cross between LP95-92 and 'Pérola'	ne[a]
51	Pérola	EPAGRI	Selection in 'Aporé'	Susceptible [5]
52	SCS 205-Riqueza	EPAGRI	Cultivar obtained from the crossing between 'BRS Campeiro' and 'IAC Tabatã'	ne[a]
53	CAV 17 EFM 0006	EPAGRI	Not available	ne[a]
54	CAV 17 EFM 0007	EPAGRI	Not available	ne[a]
55	CAV 17 EFM 008	EPAGRI	Not available	ne[a]
56	CHIB 12	EPAGRI	Access to the Epagri germplasm bank ('Banco Comprido'), collected at a Seed Fair in Canguçu, RS (2004)	ne[a]
57	CHIR 05	EPAGRI	Access to the Epagri germplasm bank ('Cavalo Mulatinho'), collected on a farmer's property in Guatambu, SC (2005)	ne[a]
58	CHIM 03	EPAGRI	Access to the Epagri germplasm bank ('Mourão'), collected on a farmer's property in Anchieta, SC (2013)	ne[a]
59	CHIR 20	EPAGRI	Access to the Epagri germplasm bank ('Bolinha'), collected on a farmer's property in Morro da Fumaça, SC (1980s)	ne[a]
60	CHIM 15	EPAGRI	Access from the Epagri germplasm bank ('Mouro'), collected in São Miguel do Oeste, SC (1993)	ne[a]

Table 1 (continued)

No.	Genotype	Germplasm bank	Genealogy/origin/characteristics	Resistance history
61	CHIP 347	EPAGRI	Access from the Epagri germplasm bank ('Manteguinha'), collected at a Seed Fair in União da Vitória, SC (1999)	ne[a]
62	CHIP 346	EPAGRI	Access from the Epagri germplasm bank ('Costa Rica'), collected at a Seed Fair in União da Vitória, SC (1999)	ne[a]
63	CHIP 334	EPAGRI	Access from the Epagri germplasm bank ('Crioulo'), collected in Anitápolis, SC (1980s)	ne[a]
64	CHC 97-29-07 -Sel. PL. Ind. V 27	EPAGRI	Lineage obtained by plant selection within access to the Epagri germplasm bank	ne[a]
65	CHC 98-42-IAC Eté × FEB 189 F9	EPAGRI	Lineage obtained from the cross between IAC Eté and CIAT FEB 183 lineage	ne[a]
66	CHC 00–101-10 Pérola × IAC F8	EPAGRI	Lineage obtained from the cross between 'Pérola' and 'IAC Eté'	ne[a]
67	CHC 01–175-2 Campe × Tiba F11	EPAGRI	Lineage obtained from the crossing between 'BRS Campeiro' and 'IAC Tibatã'	ne[a]
68	CHIP 175	EPAGRI	Access from the Epagri germplasm bank ('Preto Opaco'), obtained from a lineage from CIAT (2000)	ne[a]
69	CHIP 283	EPAGRI	Access from the Epagri germplasm bank ('Bolinha'), collected at a Seed Fair in the city of União da Vitória, PR (1999)	ne[a]
70	CHIP 305	EPAGRI	Access from the Epagri germplasm bank ('Topixaba'), collected at a Seed Fair in the city of União da Vitória, PR (1999)	ne[a]
71	CHIP 312	EPAGRI	Access to the Epagri germplasm bank, collected in an agricultural area in Alfredo Wagner, SC (collected in the 1980 s)	ne[a]
72	Cavalo Especial	EPAGRI	Access to the Epagri germplasm bank ('Banco Comprido'), collected at a Seed Fair in Canguçu, RS (2004)	ne[a]
73	ANFc09	Agro Norte Pesq. e Sem. Ltda	Not available	ne[a]
74	IAC Formoso	IAC	Cultivar obtained from the cross between Gen. 96 A28P4-1-1-1-1 and CNFC9484	ne[a]
75	IAC Diplomata	IAC	Not available	Susceptible [18]
76	Arcelin 3	IAC	Improved genotype, carrier of arcelin 3. Source of resistance to bruchids	Antixenosis [6]
77	IAC Alvorada	IAC	[G2338 (IAC Maravilha and 277)] × L317-1	Susceptible [18]
78	IPR Siriri	IAC	Cross between cultivars IAPAR 31 and IAC Akitã	ne[a]
79	Arcelin 1	IAC	Improved genotype, arcelin 1 carrier. Source of resistance to bruchids	Antixenosis [6] and Antibiosis [18]
80	Sel Especial	IAC	Source of resistance to bruchids	Antixenosis [6] and Antibiosis [18]
81	IAC Jabola	IAC	Access from Jabola Bag IAC × 'IAC Tybatã'	ne[a]
82	IAC Una[b]	IAC	Source of resistance to anthracnose (Dor 41 × H1178-100)	Susceptible [24]
83	IAC Boreal	IAC	Cultivar obtained from the cross between 'IAC Carioca Aruã' × CAL 143	ne[a]
84	IAC Harmonia	IAC	Cultivar obtained from the cross between 'IAC Carioca Aruã' × 'Iraí'	Susceptible [16]
85	CHIP 295	EPAGRI	Not available	ne[a]
86	CHIP 315	EPAGRI	Not available	ne[a]
87	CHIP 282	EPAGRI	Not available	ne[a]

Table 1 (continued)

No.	Genotype	Germplasm bank	Genealogy/origin/characteristics	Resistance history
88	CHP 01–238-10	EPAGRI	Not available	ne[a]
89	CHP 04–239-S2	EPAGRI	Not available	ne[a]
90	CHIN 19	EPAGRI	Not available	ne[a]
91	CHIP 297	EPAGRI	Not available	ne[a]
92	CHC 04–230-2	EPAGRI	Not available	ne[a]

[a] ne = not evaluated

[b] Genotype included as a susceptible standard; EPAGRI: Agricultural Research and Rural Extension Company of Santa Catarina; IAC: Agronomic Institute of Campinas

when the total number of eggs (Table 2) were considered. To a lesser extent, the genotypes CHC 04–233-2-Siriri × Horizonte, CHIB 07, CHP 01–238-80-MN13337, CAV 17 EFM0006, CHP 05–282-04-Campeiro × Agudo, IPR Tangará, TB-17-02, IPR Quero-Quero, BRS Estilo, CHIP 312, IAC Jabola, CHC 01–167-1–03, IAC Boreal, IPR Uirapuru, BRS Notável, SCS 204-Predileto, CHIR 14, CHC 01–175-1-Campeiro × IAC Tibatã exhibited a reduction in oviposition (between 95.00 and 132.25 eggs/sample) in comparison to the susceptible standard genotype (IAC Una, Table 2). A similar trend was observed in the number of viable eggs per sample (Table 2), with the exception of genotypes CHIP 312, IAC Boreal, and SCS 204-Predileto, which exhibited a large number of viable eggs and 'CNFRs-15558-Rosinha', 'IAC Imperador', and 'CHB15-518', which demonstrated a reduced number of viable eggs (Table 2). Nevertheless, no significant discrepancy was observed between the tested genotypes with regard to the number of unviable eggs (Table 2).

With regard to the F_1 progeny, the genotypes BRS Ametista, CHP 01–182-12-Uirapuru × Campeiro and BRS Esplendor stood out, showing the lowest averages for emerged adults (ranging from 11.25 to 20.50 bruchids/sample; Table 3). With an average of 26.25 to 37.00 bruchids per sample, the genotypes CHC 04–233-2-Siriri × Horizonte, CHP 05–282-04-Campeiro × Agudo, CHIB 07, IPR Uirapuru, TB-17-02, CHC 01–167-1–03, CHP 04-241 A-212-Guapo B. × Uirapuru, CHP 01–238-80-MN13337, BRS Estilo, IAC Imperador, CHIR 14, IAC Harmonia, CHC 01–175-1-Campeiro × IAC Tibatã, IPR Campos Gerais and IPR Tangará exhibited notable reductions in the F_1 progeny in comparison to susceptible standard genotype (IAC Una, Table 3).

The genotypes IAC Harmonia, CHC 01–167-1–03, Linhagem 110-IAC, IPR Uirapuru, IAC Imperador, Arcelin 1, LP 13–634-Preto, CAV 17 EFM008, IPR Campos Gerais, FAP-F3-2-SEL-IAC, BRS Ametista, CHP 05–282-04-Campeiro × Agudo, SCS 205-Riqueza, CHIR 14, TB-17-02 and CHIC 61-Cariocão exhibited the lowest percentage of larval-pupal viability (ranging from 31.69 to 46.80%) (Table 3).

Conversely, the genotypes Arcelin 1, CHP 01–182-12-Uirapuru × Campeiro, CHP 04-241 A-212-Guapo B. × Uirapuru, Arcelin 3, IPR Campos Gerais, CNFRs-15558-Rosinha, IPR Quero-Quero, BRS Esplendor, CAV 17 EFM0006, IPR Uirapuru, BRS Notável, CHV 05–268-02, CHC 01–175-1-Campeiro × IAC Tibatã, BRS Estilo, CHIN 19, and LP 13–84-Carioca were observed to significantly prolong the developmental time (cycle) of *Z. subfasciatus*, with values varying from 29.86 to 27.36 days (Table 3).

A cluster analysis considering the number of adults emerged (F_1 progeny), developmental time (cycle), larval-pupal viability, and total number of eggs resulted in three groups, with the cut-off point set at the midpoint of the maximum adjusted Euclidean distance (Fig. 1). Group I was composed of the most promising bean genotypes, including BRS Ametista, BRS Esplendor, and CHP01-182-12-Uirapuru × Campeiro. These genotypes exhibited a pronounced reduction in both the number of eggs (total and viable) and adult emergence, and demonstrated the highest level of resistance. Group II, however, was composed of 15 genotypes (BRS Estilo, TB-17-02, CHP 05–282-04-Campeiro × Agudo, IPR Tangará, CHP 01–238-80-MN13337, IPR Uirapuru, CHIB 07, CHC 04–233-2-Siriri × Horizonte, CHP 04-241 A-212-Guapo B. × Uirapuru, IAC Jabola, IPR Quero-Quero, IAC Boreal, BRS Notável, CAV17EFM0006 and CHIB312), which exhibited a lesser degree of reduction in oviposition and F_1 progeny, though still significant in comparison to Group I (Fig. 1). Finally, Group III was the most inclusive, comprising 74 genotypes. It encompassed the least promising bean genotypes, including the susceptible standard (IAC Una; Fig. 1).

4 Discussion

Our comprehensive screening of a diverse set of Brazilian bean genotypes has identified promising sources of resistance that could be utilized in breeding programs aimed at developing bean lines resistant to *Z. subfasciatus*, which represents a significant constraint in the low-altitude tropical and subtropical regions [54]. In addition, these genotypes should preferably be cultivated by small farmers in regions where this pest species is considered the most important in the post-harvest period [12]. Host resistance is emerging as an interesting biorational tool for the integrated management of stored grain insect pests in warehouses, particularly in developing countries where unsatisfactory storage infrastructure and technological limitations have resulted in significant post-harvest grain losses [29, 37].

Our results indicated a significant degree of variation in oviposition behavior among *Z. subfasciatus* specimens across the tested bean genotypes. The cultivars BRS Ametista and BRS Esplendor, as well as the bean lineages CHP 01–182-12-Uirapuru × Campeiro and CHP 04-241 A-212-Guapo B. × Uirapuru, exhibited the lowest oviposition rates, indicating the presence of high levels of antixenosis-type resistance [7]. To the best of our knowledge, this constitutes previously unreported information regarding these common bean genotypes in relation to *Z. subfasciatus*. In general,

Table 2 Means (± SE) of number of total eggs, viable eggs, and unviable eggs in different common bean genotypes[1]

Genotype	Total number of eggs	Number of viable eggs	Number of unviable eggs
CHIR 20	200.25 ± 18.38 a	124.25 ± 14.17 a	76.00 ± 13.29
IPR Siriri	190.00 ± 17.00 a	127.75 ± 14.44 a	62.25 ± 6.91
Arcelin 3	189.50 ± 32.27 a	138.00 ± 23.65 a	51.50 ± 8.98
IAC Alvorada	188.75 ± 11.16 a	127.50 ± 14.56 a	61.25 ± 7.38
CHIR 13	188.25 ± 2.90 a	110.00 ± 7.51 a	78.25 ± 6.20
CHIP 334	188.25 ± 14.10 a	120.00 ± 11.46 a	68.25 ± 10.84
CHIP 297	186.25 ± 10.87 a	123.50 ± 2.66 a	62.75 ± 9.22
CHIP 346	184.75 ± 14.33 a	123.25 ± 13.67 a	61.50 ± 2.36
IAC UNA	183.50 ± 10.69 a	115.50 ± 8.32 a	68.00 ± 13.38
Arcelin 1	181.00 ± 5.40 a	122.00 ± 7.95 a	59.00 ± 5.16
CHIN 19	181.00 ± 10.09 a	123.00 ± 6.19 a	58.00 ± 3.91
CHIP 283	180.50 ± 18.24 a	134.25 ± 19.64 a	46.25 ± 12.49
CHC 00–101-10 Pérola × IAC F8	179.50 ± 14.88 a	127.00 ± 11.39 a	52.50 ± 12.50
CHIP 295	179.00 ± 7.15 a	119.75 ± 2.65 a	59.25 ± 4.92
CHIP 315	177.25 ± 9.52 a	106.50 ± 8.87 a	70.75 ± 8.75
FAP-F3-2 Sel.- IAC	176.75 ± 10.93 a	122.00 ± 3.02 a	54.75 ± 10.88
CHIB 18	176.75 ± 7.91 a	92.75 ± 11.23 a	84.00 ± 9.12
CAV 17 EFM 008	174.00 ± 20.62 a	109.75 ± 9.50 a	64.25 ± 11.21
CHV 05–268-02	171.75 ± 23.35 a	104.50 ± 17.24 a	67.25 ± 10.14
Pérola	171.50 ± 28.31 a	112.50 ± 19.38 a	59.00 ± 9.02
LEC 04–16	170.50 ± 18.12 a	114.50 ± 4.45 a	56.00 ± 15.60
SCS 205-Riqueza	169.25 ± 15.88 a	129.25 ± 13.30 a	40.00 ± 3.67
CHC 98-42-IAC Eté × FEB 189 F9	168.50 ± 7.86 a	118.50 ± 6.27 a	50.00 ± 6.22
SM 0511-cavalo preto	167.75 ± 12.14 a	89.75 ± 12.49 a	78.00 ± 5.69
CHIP 175	167.00 ± 7.99 a	114.00 ± 9.73 a	53.00 ± 7.64
CHC 97-29-07 -Sel. PL. Ind. V 27	166.75 ± 13.69 a	123.75 ± 12.39 a	43.00 ± 6.03
CHIR 05	166.25 ± 16.13 a	109.75 ± 10.97 a	56.50 ± 5.37
CHC 04–230-2	166.25 ± 15.77 a	116.25 ± 10.89 a	50.00 ± 9.74
LP 13–624-preto	164.50 ± 15.23 a	116.50 ± 3.61 a	48.00 ± 14.80
TB-17-03	162.50 ± 16.35 a	95.00 ± 12.,62 a	67.50 ± 7.30
IAC Harmonia	162.00 ± 8.16 a	108.50 ± 6.21 a	53.50 ± 5.41
CAV 17 EFM 0007	161.75 ± 13.76 a	114.75 ± 9.65 a	47.00 ± 7.62
CHIM 03	160.75 ± 17.24 a	108.00 ± 5.99 a	52.75 ± 11.52
BRS Esteio	160.25 ± 20.99 a	100.50 ± 8.79 a	59.75 ± 12.78
CHP 04–239-S2	159.25 ± 6.80 a	98.50 ± 10.90 a	60.75 ± 6.10
Cavalo Especial	158.00 ± 16.58 a	111.25 ± 8.50 a	46.50 ± 12.86
CHIP 305	157.25 ± 18.59 a	102.75 ± 11.70 a	54.50 ± 11.49
IAC Formoso	156.50 ± 14.65 a	119.75 ± 12.78 a	36.75 ± 3.21
CHIR 04	155.50 ± 21.97 a	103.00 ± 13.64 a	52.50 ± 10.01
Linhagem 110-IAC	155.00 ± 16.61 a	104.25 ± 10.47 a	50.75 ± 9.28
CHIB 06	154.75 ± 15.14 a	93.50 ± 7.49 a	61.25 ± 9.49
CHIP 01–238-10	153.50 ± 19.47 a	103.00 ± 13.51 a	50.50 ± 9.11
CHIP 347	153.25 ± 12.59 a	91.00 ± 4.72 a	62.25 ± 15.81
CHP 01–182-48-Uirapuru × Campeiro	153.00 ± 23.16 a	90.25 ± 13.32 a	62.75 ± 10.03
IPR Tuiuiu	152.50 ± 16.29 a	108.00 ± 13.77 a	44.50 ± 5.57
CHIB 12	151.75 ± 10.68 a	114.25 ± 7.13 a	37.50 ± 9.49
BRS Campeiro	151.00 ± 11.31 a	85.75 ± 11.65 a	65.25 ± 1.14
SCS 206-Potência	151.00 ± 7.15 a	90.75 ± 3.90 a	60.25 ± 3.90
CHIP 282	150.75 ± 12.12 a	92.75 ± 11.69 a	58.00 ± 10.14
IPR Garça	150.50 ± 13.26 a	93.50 ± 5.77 a	57.00 ± 8.57
IAC Diplomata	150.00 ± 13.98 a	101.75 ± 12.95 a	48.25 ± 2.97

Table 2 (continued)

Genotype	Total number of eggs	Number of viable eggs	Number of unviable eggs
CHIM 15	148.75 ± 8.53 a	112.25 ± 1.88 a	36.50 ± 8.95
CNFRj-15411-rajado	148.50 ± 19.58 a	86.00 ± 16.04 a	62.50 ± 11.98
BRS Radiante	148.00 ± 12.30 a	93.50 ± 10.76 a	54.50 ± 11.43
SM 1510-preto	147.75 ± 16.42 a	82.25 ± 13.17 a	65.50 ± 9.30
CHB 15–518	147.75 ± 22.24 a	67.25 ± 9.19 b	80.50 ± 13.29
UEM 266	147.00 ± 10.61 a	91.25 ± 10.85 a	55.75 ± 5.14
CHB 15–519	145.50 ± 7.42 a	85.50 ± 3.11 a	60.00 ± 9.13
Arcelin 4	145.50 ± 28.50 a	81.00 ± 12.89 a	64.50 ± 17.33
CHC 01–175-2 Campe × Tiba F11	140.00 ± 17.07 a	93.50 ± 9.14 a	46.50 ± 8.14
CHV 17–641	139.75 ± 5.42 a	98.25 ± 3.70 a	41.50 ± 3.54
ANFc09	138.50 ± 7.96 a	95.25 ± 4.60 a	43.25 ± 3.36
LP 13–84-carioca	138.25 ± 17.25 a	88.75 ± 13.90 a	49.50 ± 4.13
IAC Imperador	138.25 ± 16.63 a	79.50 ± 10.87 b	58.75 ± 10.80
CHIB 11	138.00 ± 13.54 a	92.75 ± 11.99 a	45.25 ± 4.84
CHV 17–635	137.50 ± 18.81 a	91.50 ± 11.54 a	46.00 ± 10.09
CNFRs-15,558-rosinha	137.25 ± 14.90 a	77.75 ± 9.64 b	59.50 ± 6.64
CHIC 61-Cariocão	136.25 ± 14.57 a	88.00 ± 7.56 a	48.25 ± 8.61
IPR Campos Gerais	135.50 ± 8.58 a	81.75 ± 7.13 a	53.75 ± 7.97
Avaluna	134.75 ± 13.25 a	93.25 ± 5.21 a	41.50 ± 10.81
CHC 01–175-1-Campeiro × IAC Tibatã	132.25 ± 11.69 b	73.75 ± 11.15 b	58.50 ± 6.43
CHIR 14	130.25 ± 17.56 b	70.75 ± 8.92 b	59.50 ± 11.37
SCS 204-Predileto	129.00 ± 12.36 b	81.50 ± 8.32 a	47.50 ± 8.16
BRS Notável	124.00 ± 19.75 b	69.50 ± 11.76 b	54.50 ± 14.62
IPR Uirapuru	122.00 ± 15.35 b	77.75 ± 12.41 b	44.25 ± 13.58
IAC Boreal	121.50 ± 18.11 b	82.00 ± 11.62 a	39.50 ± 7.76
CHC 01–167-1–03	120.75 ± 26.26 b	80.75 ± 21.11 b	40.00 ± 14.40
IAC Jabola	118.75 ± 14.22 b	74.25 ± 9.48 b	44.50 ± 7.46
CHIP 312	117.50 ± 22.82 b	83.25 ± 13.99 a	34.25 ± 11.59
BRS Estilo	117.25 ± 25.73 b	63.75 ± 16.52 b	53.50 ± 11.03
IPR Quero-Quero	117.25 ± 25.71 b	68.75 ± 18.47 b	48.50 ± 11.39
TB-17-02	116.75 ± 13.99 b	63.25 ± 4.01 b	53.50 ± 11.70
IPR Tangará	109.00 ± 8.74 b	67.25 ± 8.17 b	41.75 ± 0.65
CHP 05–282-04-Campeiro × Agudo	107.75 ± 30.05 b	61.25 ± 16.83 b	46.50 ± 13.29
CAV 17 EFM 0006	107.75 ± 14.86 b	62.00 ± 10.83 b	45.75 ± 11.15
CHP 01–238-80-MN 13337	102.75 ± 18.95 b	57.00 ± 8.91 b	45.75 ± 11.71
CHIB 07	96.50 ± 16.08 b	54.25 ± 15.35 b	42.25 ± 5.81
CHC 04–233-2-Siriri × Horizonte	95.00 ± 13.11 b	50.50 ± 8.00 b	44.50 ± 7.15
CHP 04-241 A-212-Guapo B. × Uirapuru	81.75 ± 24.57 c	48.75 ± 15.68 b	33.00 ± 10.40
BRS Esplendor	60.75 ± 15.87 c	36.25 ± 10.03 b	24.50 ± 6.14
CHP 01–182-12-Uirapuru × Campeiro	48.75 ± 13.72 c	15.75 ± 5.54 b	33.00 ± 8.72
BRS Ametista	41.50 ± 12.34 c	25.25 ± 7.72 b	16.25 ± 5.50
F	1.3501	4.1894	1.2559
df	91,276	91,276	91, 276
p-value	0.03552	< 0.0001	0.0831[ns]
CV (%)	25.27	14.84	22.09

[1] Means within the columns followed by the same letters do are not significantly different by the Skott-Knott test ($p < 0.05$). Original data presented in the table. For the analysis, data were transformed using the optimal power method of Box and Cox (1964)

[ns] Non-significant

Table 3 Means (± SE) of emerged adults, larval-pupal viability (%) and developmental time (days) of *Zabrotes subfasciatus* in different common bean genotypes[1]

Genotype	Number of emerged adults	Larval-pupal viability (%)	Developmental time (days)
CHIR 20	82.75 ± 11.08 a	66.32 ± 2.67 a	26.00 ± 0.37 b
IPR Siriri	100.50 ± 13.44 a	78.06 ± 2.54 a	26.52 ± 0.52 b
Arcelin 3	96.75 ± 14.68 a	71.68 ± 3.41 a	29.14 ± 0.64 a
IAC Alvorada	98.75 ± 8.06 a	78.59 ± 2.68 a	26.01 ± 0.38 b
CHIR 13	64.50 ± 4.78 b	58.73 ± 2.11 b	26.70 ± 0.98 b
CHIP 334	79.50 ± 6.57 a	68.17 ± 7.11 a	25.93 ± 0.29 b
CHIP 297	93.00 ± 5.52 a	75.19 ± 3.71 a	25.44 ± 0.13 b
CHIP 346	83.75 ± 11.00 a	67.48 ± 3.24 a	26.94 ± 0.77 b
IAC UNA	83.75 ± 7.86 a	73.51 ± 7.80 a	26.14 ± 0.34 b
Arcelin 1	49.75 ± 7.16 c	40.36 ± 4.56 c	29.86 ± 1.22 a
CHIN 19	92.50 ± 4.10 a	76.42 ± 6.42 a	27.42 ± 0.51 a
CHIP 283	90.25 ± 11.02 a	68.87 ± 4.78 a	25.88 ± 0.57 b
CHC 00–101-10 Pérola × IAC F8	106.00 ± 9.76 a	83.57 ± 2.91 a	26.88 ± 0.61 b
CHIP 295	80.50 ± 3.56 a	67.24 ± 2.65 a	25.81 ± 0.37 b
CHIP 315	77.25 ± 3.88 a	75.20 ± 8.47 a	26.56 ± 0.79 b
FAP-F3-2 Sel.- IAC	54.00 ± 2.32 b	44.26 ± 1.52 c	26.09 ± 0.48 b
CHIB 18	57.25 ± 6.77 b	62.46 ± 4.31 a	26.01 ± 0.37 b
CAV 17 EFM 008	47.00 ± 5.02 c	43.14 ± 3.62 c	26.22 ± 0.65 b
CHV 05–268-02	61.50 ± 9.50 b	59.47 ± 1.41 b	27.47 ± 1.38 a
Pérola	61.75 ± 8.86 b	57.82 ± 6.36 b	26.05 ± 0.27 b
LEC 04–16	71.00 ± 6.29 b	62.97 ± 7.37 a	25.71 ± 0.13 b
SCS 205-Riqueza	57.75 ± 5.27 b	45.33 ± 2.77 c	26.06 ± 0.25 b
CHC 98-42-IAC Eté × FEB 189 F9	87.25 ± 7.21 a	58.08 ± 11.50 b	32.03 ± 0.63 b
SM 0511-cavalo preto	42.75 ± 4.72 c	74.36 ± 7.61 a	26.19 ± 0.44 b
CHIP 175	79.75 ± 7.88 a	70.11 ± 4.18 a	26.83 ± 1.00 b
CHC 97-29-07 -Sel. PL. Ind. V 27	79.00 ± 12.11 a	64.36 ± 7.14 a	26.32 ± 0.50 b
CHIR 05	65.00 ± 4.03 b	60.94 ± 5.49 b	25.91 ± 0.35 b
CHC 04–230-2	83.75 ± 10.16 a	71.68 ± 5.63 a	25.80 ± 0.12 b

Table 3 (continued)

Genotype	Number of emerged adults	Larval-pupal viability (%)	Developmental time (days)
LP 13–624-preto	48.00 ± 9.82 c	41.52 ± 8.49 c	26.72 ± 0.32 b
TB-17-03	54.00 ± 5.51 b	58.23 ± 5.08 b	26.70 ± 0.34 b
IAC Harmonia	33.75 ± 5.25 d	31.69 ± 5.41 c	26.01 ± 0.32 b
CAV 17 EFM 0007	75.25 ± 8.67 a	66.11 ± 6.22 a	26.59 ± 0.77 b
CHIM 03	74.75 ± 3.03 a	69.55 ± 1.89 a	26.75 ± 1.12 b
BRS Esteio	65.00 ± 8.82 b	64.08 ± 4.37 a	26.80 ± 0.88 b
CHP 04–239-S2	69.50 ± 6.62 b	71.62 ± 4.11 a	26.17 ± 0.35 b
Cavalo Especial	92.50 ± 9.71 a	71.62 ± 4.11 a	26.17 ± 0.35 b
CHIP 305	78.25 ± 7.21 a	76.86 ± 2.84 a	25.94 ± 0.30 b
IAC Formoso	93.25 ± 8.47 a	78.43 ± 1.99 a	26.41 ± 0.44 b
CHIR 04	57.50 ± 8.76 b	57.15 ± 6.41 a	25.40 ± 0.23 b
Linhagem 110-IAC	41.00 ± 10.85 c	38.20 ± 7.86 c	26.53 ± 0.94 b
CHIB 06	47.50 ± 6.33 c	50.23 ± 3.71 b	26.40 ± 0.65 b
CHIP 01–238-10	64.75 ± 6.94 b	64.85 ± 4.96 a	25.99 ± 0.32 b
CHIP 347	72.75 ± 6.25 b	81.11 ± 8.69 a	26.20 ± 0.39 b
CHP 01–182-48-Uirapuru × Campeiro	51.00 ± 10.89 c	54.15 ± 4.10 b	27.23 ± 0.66 b
IPR Tuiuiu	62.00 ± 6.39 b	58.27 ± 2.10 b	25.91 ± 0.27 b
CHIB 12	92.25 ± 9.83 a	79.98 ± 4.08 a	27.03 ± 1.16 b
BRS Campeiro	47.00 ± 5.78 c	55.90 ± 5.82 b	25.98 ± 0.43 b
SCS 206-Potência	47.75 ± 3.86 c	52.98 ± 4.91 b	26.92 ± 0.90 b
CHIP 282	66.00 ± 2.94 b	73.62 ± 5.01 a	25.93 ± 0.32 b
IPR Garça	56.00 ± 6.19 b	59.63 ± 5.38 b	25.48 ± 0.04 b
IAC Diplomata	67.75 ± 9.59 b	66.11 ± 1.01 a	25.62 ± 0.38 b
CHIM 15	68.00 ± 3.18 b	60.80 ± 3.62 b	26.81 ± 0.61 b
CNFRj-15,411-rajado	47.25 ± 7.18 c	56.80 ± 6.44 b	26.17 ± 0.23 b
BRS Radiante	57.25 ± 9.54 b	61.33 ± 6.17 b	26.01 ± 0.27 b

Table 3 (continued)

Genotype	Number of emerged adults	Larval-pupal viability (%)	Developmental time (days)
SM 1510-preto	51.50 ± 3.56 c	67.08 ± 8.21 a	26.15 ± 0.20 b
CHB 15–518	53.00 ± 13.12 c	73.77 ± 9.68 a	26.74 ± 0.64 b
UEM 266	59.00 ± 6.77 b	66.12 ± 6.93 a	26.60 ± 0.76 b
CHB 15–519	66.00 ± 2.81 b	77.32 ± 2.69 a	25.83 ± 0.46 b
Arcelin 4	46.00 ± 11.71 c	54.86 ± 6.46 b	27.24 ± 0.36 b
CHC 01–175-2 Campe × Tiba F11	62.25 ± 2.51 b	68.06 ± 4.00 a	26.29 ± 0.80 b
CHV 17–641	50.25 ± 2.72 c	51.06 ± 1.40 b	25.91 ± 0.27 b
ANFc09	70.25 ± 3.76 b	74.22 ± 4.47 a	27.10 ± 1.04 b
LP 13–84-carioca	50.75 ± 7.81 c	57.47 ± 2.74 b	27.36 ± 0.49 a
IAC Imperador	32.25 ± 5.89 d	39.69 ± 5.54 c	27.26 ± 0.73 b
CHIB 11	66.50 ± 8.88 b	71.73 ± 1.39 a	26.16 ± 0.65 b
CHV 17–635	57.25 ± 7.94 b	64.61 ± 7.70 a	26.64 ± 0.54 b
CNFRs-15558-rosinha	46.00 ± 4.08 c	60.77 ± 4.34 b	28.36 ± 1.22 a
CHIC 61-Cariocão	41.25 ± 4.52 c	46.80 ± 3,18 c	26.30 ± 0.21 b
IPR Campos Gerais	36.50 ± 7.02 d	43.75 ± 5.48 c	28.41 ± 1.65 a
Avaluna	49.50 ± 7.28 c	53.03 ± 6.92 b	26.69 ± 1.02 b
CHC 01–175-1-Campeiro × IAC Tibatã	36.00 ± 5.40 d	50.29 ± 5.45 b	27.44 ± 0.68 a
CHIR 14	33.50 ± 5.93 d	46.16 ± 5.37 c	26.18 ± 0.39 b
SCS 204-Predileto	50.50 ± 8.82 c	60.68 ± 5.64 b	26.04 ± 0.43 b
BRS Notável	57.75 ± 10.63 b	82.25 ± 5.30 a	27.89 ± 1.01 a
IPR Uirapuru	29.25 ± 5.75 d	38.70 ± 6.26 c	28.16 ± 0.35 a
IAC Boreal	55.75 ± 8.38 b	68.43 ± 3.77 a	25.40 ± 0.26 b
CHC 01–167-1–03	30.25 ± 9.98 d	36.99 ± 9.31 c	26.92 ± 0.27 b
IAC Jabola	53.75 ± 4.04 b	75.13 ± 7.36 a	25.40 ± 0.32 b
CHIP 312	49.25 ± 10.42 c	56.52 ± 4.49 b	26.64 ± 0.10 b
BRS Estilo	32.50 ± 9.42 d	51.23 ± 6.15 b	27.43 ± 0.93 a
IPR Quero-Quero	49.25 ± 13.52 c	71.39 ± 9.75 a	28.26 ± 0.71 a
TB-17-02	29.75 ± 3.65 d	46.45 ± 2.76 c	26.88 ± 0.39 b
IPR Tangará	37.00 ± 9.55 d	52.75 ± 8.82 b	27.05 ± 0.74 b
CHP 05–282-04-Campeiro × Agudo	28.50 ± 7.94 d	45.05 ± 2.46 c	26.77 ± 0.16 b

Table 3 (continued)

Genotype	Number of emerged adults	Larval-pupal viability (%)	Developmental time (days)
CAV 17 EFM 0006	49.25 ± 5.89 c	83.10 ± 5.59 a	28.20 ± 0.88 a
CHP 01–238-80-MN 13337	32.00 ± 7.52 d	53.46 ± 5.61 b	26.46 ± 0.46 b
CHIB 07	29.25 ± 7.96 d	56.06 ± 3.79 b	26.90 ± 0.41 b
CHC 04–233-2-Siriri × Horizonte	26.25 ± 3.45 d	54.09 ± 7.09 b	26.35 ± 1.70 b
CHP 04-241 A-212-Guapo B. × Uirapuru	30.75 ± 11.50 d	59.64 ± 4.17 b	29.20 ± 1.11 a
BRS Esplendor	20.50 ± 5.54 e	57.78 ± 3.22 b	28.23 ± 0.93 a
CHP 01–182-12-Uirapuru × Campeiro	12.00 ± 3.57 e	85.52 ± 7.49 a	29.84 ± 0.71 a
BRS Ametista	11.25 ± 3.03 e	45.00 ± 6.10 c	27.18 ± 0.22 b
F	8.8427	3.8123	1.4644
df	91,276	91,276	91,276
p-value	< 0.0001	< 0.0001	0.010049
CV (%)	16.86	20.75	5.76

[1] Means within the columns followed by the same letters do are not significantly different by the Skott-Knott test ($p < 0.05$). Original data presented in the table. For the analysis, data were transformed using the optimal power method of Box and Cox [11]]

[ns] Non-significant

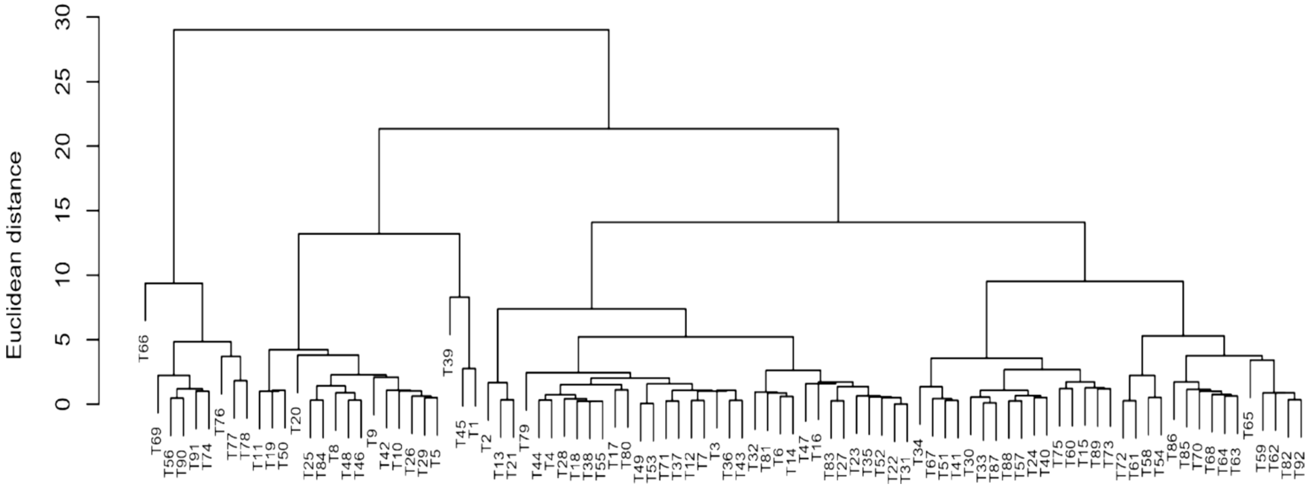

Fig. 1 Dendrogram obtained from the cluster analysis based on similarity of larval-pupal viability, number of emerged adults, developmental time (cycle), and total number of eggs of *Zabrotes subfasciatus* on common bean (*Phaseolus vulgaris* L., Fabaceae) genotypes. The mean Euclidean distance was used as a measure of dissimilarity and the average method as a clustering strategy (the cut-off point was established considering half of maximum adjusted Euclidian distance). Obs.: For details of genotype number, please see Table 1

the antixenosis-type resistance influences the host selection behavior of stored pests and is generally related to physical, chemical, and morphological traits, including the size and color of the seeds [23, 55], the thickness of the tegument [4], the grain surface texture [53], and the production of semiochemicals (volatile compounds) that mediate the host selection by bruchids [41].

The findings of Cabral et al. [12]] corroborate those presented here. They also verified a reduction in oviposition of *Acanthoscelides obtectus* (Say) (Coleoptera: Chrysomelidae: Bruchinae) in the BRS Ametista genotype. The same authors verified that, although the BRS Esplendor genotype did not exhibit a reduction in oviposition, it did promote a considerable reduction in the number of emerged adults, demonstrating a species-specific bruchid relationship. With regard to other pest species of agricultural relevance, the same genotypes (BRS Ametista and BRS Esplendor) were found to be the least utilized for oviposition and nymph establishment of *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) Middle East Asia Minor 1 [49]. In addition, this common bean cultivar is resistant to anthracnose and Fusarium wilt [36], making it an interesting option for cultivation, particularly among smallholder farmers in Brazil and elsewhere.

By employing a metabolomic approach through headspace solid-phase coupled with gas chromatography-mass spectrometry (HS-SPME-GC-MS) analysis, Lamz-Piedra et al. [31] successfully identified the volatile compounds dimethyl disulfide, limone, (E)−2-hexenal, and hexanal as potential antixenotic factors in resistant common bean genotypes to *Z. subfasciatus*. The olfactory cues that attract weevils to dry beans have been previously documented [12], yet further studies are necessary to fully elucidate the factors involved in the antixenosis-type resistance observed in these promising genotypes.

The findings of our study, particularly the lower rates of adult emergence and the considerable reduction in larval-pupal viability, especially in the genotypes BRS Ametista and BRS Esplendor, as well as the prolongation of developmental time (biological cycle) observed in the genotypes Arcelin 1, CHP 01–182-12-Uirapuru × Campeiro, CHP 04-241 A-212-Guapo B. × Uirapuru, Arcelin 3, IPR Campos Gerais, CNFRs-15558-Rosinha, IPR Quero-Quero, BRS Esplendor, CAV 17 EFM0006, IPR Uirapuru, BRS Notável, CHV 05–268-02, CHC 01–175-1-Campeiro × IAC Tibatã, BRS Estilo, CHIN 19, and LP 13–84-Carioca suggested the expression of resistance by antibiosis and/or antixenosis [7]. In general, a set of morphological and chemical factors are probably related to antibiosis type resistance, including alterations in nutritive and non-nutritive compounds.

Toxic compounds (allelochemicals), such as antibiotics, alkaloids, terpenes, and cyanogenic glycosides [47], have the potential to impede the development of immature stages and reduce larval-pupal viability [12]. Furthermore, seed storage proteins produced by the APA (arcelin, phytohemagglutinin, and α-amylase inhibitor) gene family [1, 32, 34] are described in resistant genotypes and affect the proportion of emergence of adult bruchids, as well as hindering insect growth and development [43]. Boiça Júnior et al. [10] proposed that the high crude protein content may serve as a potential defense mechanism underlying the resistance of common beans to *Z. subfasciatus*. In a more recent study, Maro et al. [34] identified arcelin 5, leucoagglutinin, erythroagglutinin, and a hypothetical seed storage protein (26 kDa) as potential antibiosis resistance mechanisms in Malawian common bean landraces. In bean genotypes, eight variants of arcelin (Arc-1 to Arc-8) were identified [56], and their presence was associated with bean resistance to *Z. subfasciatus* in wild landraces or cultivars. The arcelin genes were mapped on chromosome 4 of the common bean genome [42]. The mode of action of arcelin is likely associated with the disruption of epithelial cells in the insect gut or may even function as a source of poorly digestible protein [14]. This disrupts nutrient assimilation, which delays insect development or causes death at different stages [3].

As stated by Cardona et al. [13], Arcelin 5 and Arcelin 1 exhibit the highest level of resistance to *Z. subfasciatus* in common bean accessions, followed by Arcelin 4, Arcelin 2, and Arcelin 3 in the descending order of importance. The same was observed in our comprehensive screening, in which three breeding lines containing variants of arcelin (1, 3, and 4) were assessed. The Arcelin 1 line was identified as the most promising, exhibiting a reduction in adult emergence and larval-pupal viability, along with an increase in the developmental time. To a lesser extent, Arcelin 4 also affected the bruchid emergence and larval-pupal viability, while the Arcelin 3 breeding line only increased the biological cycle of *Z. subfasciatus*. In general, arcelin expression is inherited as a monogenic dominant trait [28], and consequently, it can be easily transferred to commercial cultivars through backcrossing. This potential should be further explored in breeding programs.

In conclusion, our comprehensive screening of a diverse set of Brazilian common bean genotypes identified promising sources of resistance to *Z. subfasciatus*, paving the way for further research aimed at characterizing the types and mechanisms involved in the most promising genotypes. It is important to highlight that an understanding of the molecular basis of resistance will facilitate the identification of the resistance genes/QTLs through the use of genome sequence data, which can then be introgressed into cultivated varieties through marker-assisted backcross breeding [30]]. Improved genotypes should be an integral part of an IPM strategy for stored pests, contributing to the reduction of food loss and the mitigation of environmental and ecotoxicological risks associated with the excessive use of synthetic insecticides, while also ensuring food security.

Author contributions L.P.R., E.L.L.B. and J.D.V. conceived the study; V.S.O.T., I.R.C., R.D.F. AND V.F.C. conducted the laboratory assays; L.P.R. and V.S.O.T. analyzed the data; V.S.O.T. and L.P.R. write the draft manuscript and all authors contributed to improving and reviewing the paper. All authors have read and agreed to the published version of the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate The germplasm (seeds) used in the present study were obtained from the germplasm banks of the Agronomic Institute of Campinas (IAC) and the Agricultural Research and Rural Extension Company of Santa Catarina (CEPAF/EPAGRI). Therefore, the procedure used in the study complies with local or national guidelines, with no need for further affirmation. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the institutions that provided the seeds employed in this study.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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