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Genetics/ Original Article

## Fuzzy logic applied to different adaptability and stability methods in common bean








**Abstract** – The objective of this work was to evaluate the efficiency of the methods of Eberhart & Russell and Lin & Binns, modified for the automation of decision-making by fuzzy logic, in assessing the adaptability and stability of common bean (*Phaseolus vulgaris*) cultivars. Eighteen cultivars of the “carioca” commercial group were evaluated in 11 environments, in Brazil. All results were obtained by programming in the R software. The developed controllers were based on the fuzzy inference system developed by Mamdani. This system was modeled to enable interpretations of the method of Eberhart & Russell alone or together with the modified method of Lin & Binns. The controller based on Eberhart & Russell and the one based on Eberhart & Russell and Lin & Binns identified the same cultivars as having general adaptability, but differed as to the classification of cultivars adapted to unfavorable environments. The BRSMG Pioneiro, BRS Pontal, IAC-Carioca Tybatã, and IPR Juriti cultivars presented general adaptability, whereas Campeão, Pérola, and BRS Estilo showed specific adaptability to favorable environments. The fuzzy logic methods used are efficient and allow the classification of all evaluated cultivars.

**Index terms:** computational intelligence, fuzzy logic and automation, genetic improvement, genotype by environment interaction.

### Lógica difusa aplicada a diferentes métodos de adaptabilidade e estabilidade no feijoeiro-comum

**Resumo** – O objetivo deste trabalho foi avaliar a eficiência dos métodos de Eberhart & Russell e Lin & Binns, modificados para automação da tomada de decisão pela lógica difusa, na avaliação da adaptabilidade e da estabilidade de cultivares de feijoeiro-comum (*Phaseolus vulgaris*). Foram avaliadas 18 cultivares do grupo comercial carioca em 11 ambientes, no Brasil. Todos os resultados foram obtidos por programação no programa R. Os controladores desenvolvidos foram fundamentados no sistema de inferência difusa desenvolvido por Mamdani. Este sistema foi modelado para possibilitar interpretações do método de Eberhart & Russell isoladamente ou em conjunto com o método de Lin & Binns modificado. O controlador baseado em Eberhart & Russell e o baseado em Eberhart & Russell e Lin & Binns identificaram as mesmas cultivares como tendo adaptabilidade geral, mas diferiram quanto à classificação das cultivares adaptadas a ambientes desfavoráveis. As cultivares BRSMG Pioneiro, BRS Pontal, IAC-Carioca Tybatã e IPR Juriti apresentaram adaptabilidade geral, enquanto Campeão, Pérola e BRS Estilo mostraram adaptabilidade específica a ambientes favoráveis. Os métodos de lógica difusa utilizados mostram eficiência e possibilitam a classificação de todas as cultivares avaliadas.


**Termos para indexação:** inteligência computacional, lógica difusa e automação, melhoramento genético, interação genótipo com ambiente.

Anna Regina Tiago Carneiro<sup>(1)</sup> ,  
Demerson Arruda Sanglard<sup>(1)</sup> ,  
Alcinei Místico Azevedo<sup>(1)</sup> ,  
Thiago Lívio Pessoa Oliveira de Souza<sup>(2)</sup> ,  
Helton Santos Pereira<sup>(2)</sup> ,  
Leonardo Cunha Melo<sup>(2)</sup> ,  
Pedro Crescêncio Souza Carneiro<sup>(3)</sup> 

<sup>(1)</sup> Universidade Federal de Minas Gerais, Instituto de Ciências Agrárias, Avenida Universitária, Campus Regional de Montes Claros, nº 1.000, Universitário, CEP 39404-547 Montes Claros, MG, Brazil. E-mail: [anna-regina@hotmail.com](mailto:anna-regina@hotmail.com), [demerson.ufmg@gmail.com](mailto:demerson.ufmg@gmail.com), [alcineimistico@hotmail.com](mailto:alcineimistico@hotmail.com)

<sup>(2)</sup> Embrapa Arroz e Feijão, Rodovia GO-462, Km 12, Fazenda Capivara, Zona Rural, Caixa Postal 179, CEP 75375-000 Santo Antônio de Goiás, GO, Brazil. E-mail: [thiago.souza@embrapa.br](mailto:thiago.souza@embrapa.br), [helton.pereira@embrapa.br](mailto:helton.pereira@embrapa.br), [leonardo.melo@embrapa.br](mailto:leonardo.melo@embrapa.br)

<sup>(3)</sup> Universidade Federal de Viçosa, Avenida Peter Henry Rolfs, s/nº, Campus Universitário, CEP 36570-900 Viçosa, MG, Brazil. E-mail: [carneiro@ufv.br](mailto:carneiro@ufv.br)

 Corresponding author

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## Introduction

Common bean (*Phaseolus vulgaris* L.) is a crop of great social and economic importance for Brazil, as it is a staple food in the diet of the population. It is cultivated in practically all regions of the country by small and large producers in different production systems and crop seasons (Vieira et al., 2013).

Due to the diverse conditions for common bean cultivation, the interaction between genotypes and environments can affect the chosen cultivars (Borém & Miranda, 2013). Among the alternatives to better understand the effect of this interaction, stand out the analysis of genotype adaptability and phenotypic stability (Cruz et al., 2012).

Although important and essential in plant breeding, these methodologies are complicated and difficult to interpret, hindering the breeder's decision-making process. When there is a large number of genotypes and environments, for example, several parameters should be evaluated in isolation for each genotype, in order to select the best one. In this context, Carneiro et al. (2018) proposed fuzzy control systems as a tool to assist in decision-making in adaptability and stability studies. Fuzzy logic translates numeric values into verbal, vague, imprecise, and qualitative expressions common in communication, allowing to convert human experience into a computer-decodable language (Simões & Shaw, 2007), which can be applied in automation in several areas. Therefore, fuzzy logic has great potential in studies of adaptability and stability, as a tool to interpret the parameters of the used methods and, consequently, to automate decisions that would be made by the breeders (Carneiro et al., 2018). This allows transforming a previously time-consuming and laborious process into a simple, practical, and fast one.

Even though the work of Carneiro et al. (2018) has shown the efficiency of the method of Eberhart & Russell in the automation of decision-making, it is important to test it with other experimental data, as well as to check the efficiency of fuzzy logic for other methodologies, such as that of the method of Lin & Binns.

The objective of this work was to evaluate the efficiency of the methods of Eberhart & Russell and Lin & Binns, modified for the automation of decision-making by fuzzy logic, in assessing the adaptability and stability of common bean cultivars.

## Materials and Methods

The data used in the study were obtained from experiments carried out within the common bean breeding program of Embrapa Arroz e Feijão, with the following 18 common bean cultivars of the "carioca" commercial group: Alba, BRS 9435 Cometa, BRS Estilo, BRS Horizonte, BRSMG Majestoso, BRSMG Pioneiro, BRSMG Talismã, BRS Pontal, BRS Requite, Campeão, SCS202 Guará, IAC-Carioca Tybatã, IPR Colibri, IPR Juriti, IPR Saracura, FTS Magnífico, Pérola, and Rubi.

The trials were conducted in 11 environments, in the municipalities of: Ponta Grossa, in the state of Paraná (25°5'40"S, 50°09'48"W); Santo Antônio de Goiás, in the state of Goiás (16°28'00"S, 49°17'00"W); and Uberlândia, in the state of Minas Gerais (18°54'44"S, 48°15'44"W), in the rainy, dry, and winter crop seasons, in 2006, 2007, 2008, and 2010. The combination of each location, crop, and year was considered as a growing environment. Each environment, its climatic characteristics, and location are described in Table 1. The experimental design was a randomized complete block, with three replicates. The experimental units consisted of four lines of 4.0 m, spaced at 0.50 m. Productivity data were collected in the two central lines of the plots, whose grain yield was measured and converted, in kg ha<sup>-1</sup>, to 13% humidity.

The data were subjected to the analysis of individual variance, according to the model:  $Y_{ij} = \mu + G_i + B_j + \varepsilon_{ij}$ , where  $Y_{ij}$  is the value of each character for the  $i$ th genotype in the  $j$ th block;  $\mu$  is the overall average;  $G_i$  is the effect of the  $i$ th genotype;  $B_j$  is the effect of the  $j$ th block; and  $\varepsilon_{ij}$  is the random error. The mean squares of the residues showed homogeneity between the experiments, with a ratio less than seven between the largest and the smallest mean square. This enabled a joint analysis, based on the following statistical model (Pimentel-Gomes, 2009):  $Y_{ijk} = \mu + (b/a)_{ijk} + g_i + a_j + g_{aij} + \varepsilon_{ijk}$ , where  $Y_{ijk}$  is the observation in the  $k$ th block, evaluated in the  $i$ th genotype and  $j$ th environment;  $\mu$  is the overall average;  $(b/a)_{ijk}$  is the effect of block  $k$  within environment  $j$ ;  $g_i$  is the effect of genotype  $i$ ;  $a_j$  is the effect of environment  $j$ ;  $g_{aij}$  is the effect of the interaction between genotype  $i$  and environment  $j$ ; and  $\varepsilon_{ijk}$  is the random error associated with observation  $ijk$ .

Analyses of adaptability and stability were also performed by the method of Eberhart & Russell (1966)

and the method of Lin & Binns (1988) modified by Carneiro (1988).

The data were subjected to the analysis of adaptability and stability by the method of Eberhart & Russell, based on the statistical model:  $\bar{Y}_{ij} = \beta_{0i} + \beta_{1i}I_j + \delta_{ij} + \varepsilon_{ij}$ , where  $\bar{Y}_{ij}$  is the estimated mean of cultivar  $i$  in environment  $j$ ;  $\beta_{0i}$  is the mean of genotype  $i$  in all environments;  $\beta_{1i}$  is the linear regression coefficient of cultivar  $i$ , which measures the response of the  $i$ th genotype to the variation of the environment;  $I_j$  is the coded environmental index;  $\delta_{ij}$  is the deviation of the regression of the cultivar; and  $\varepsilon_{ij}$  is the mean experimental error.

For the modified method of Lin & Binns, the  $P_{ij}$  measure was decomposed into favorable ( $P_{if}$ ) and unfavorable ( $P_{id}$ ) environments.

For the favorable environments (environmental index  $\geq 0$ ), the parameter was estimated as:

$$P_{if} = \frac{\sum_{j=1}^f (Y_{if} - M_{.j})^2}{2.f}$$

where  $P_{if}$  is the measure of adaptability and stability of genotype behavior in favorable environment  $i$ ;  $Y_{ij}$  is the productivity of the  $i$ th genotype, in the  $j$ th environment;  $M_j$  is the maximum response among all genotypes in the environment; and  $f$  is the number of favorable environments.

For the unfavorable environments (environmental index  $\leq 0$ ), the parameter was estimated as:

$$P_{id} = \frac{\sum_{j=1}^d (Y_{ij} - M_{.j})^2}{2.d}$$

where  $P_{id}$  is the measure of adaptability and stability of genotype behavior in unfavorable environment  $i$ ;  $Y_{ij}$  is the productivity of the  $i$ th genotype in the  $j$ th environment;  $M_j$  is the maximum response among all genotypes in the environment; and  $d$  is the number of unfavorable environments.

For the method of Eberhart & Russell, a fuzzy controller, based on the fuzzy inference system proposed by Mamdani & Assilian (1975), was developed. The input fuzzy linguistic variables used were: general mean parameter ( $\beta_0$ ), regression coefficient ( $\beta_1$ ), and coefficient of determination ( $R^2$ ). Fuzzy sets were generated for each variable through pertinence functions (Carneiro et al., 2018).

The general averages of the genotypes were standardized on a scale from 0 to 100. Standardization was based on the normal distribution of data, overall mean value ( $\mu$ ), and standard deviation ( $\sigma$ ). The values associated with  $\mu - 3\sigma$  were assigned the value of 0, and those associated with  $\mu + 3\sigma$  were assigned the value of 100.

The values of  $\beta_1$  were allocated into the following sets: less than 1, equal to 1, and greater than 1, using Z-,  $\pi$ -, and S-shaped functions (Carneiro et al., 2018), respectively.

**Table 1.** Environments, climate data, crop season, and year of cultivation of the trials with common bean (*Phaseolus vulgaris*) cultivars, of the “carioca” commercial group, carried out in three Brazilian municipalities in 2006, 2007, 2008, and 2010.

Environment	Location <sup>(1)</sup>	Elevation <sup>(2)</sup> (m)	Climate data (annual average) <sup>(3)</sup>			Harvest period <sup>(5)</sup>	Year
			Precipitation <sup>(4)</sup> (mm)	RH (%)	Temperature (°C)		
1	L1	956	473.7	76.4	16.5	Rainy	2006
2	L1	956	533.5	80.2	17.0	Rainy	2008
3	L1	956	418.6	73.0	16.1	Rainy	2010
4	L1	956	625.3	81.1	21.0	Dry	2007
5	L1	956	766.0	84.0	20.0	Dry	2010
6	L2	823	226.1	55.5	22.5	Winter	2006
7	L2	823	255.2	57.2	22.2	Winter	2008
8	L2	823	202.3	50.5	23.5	Winter	2010
9	L3	870	142.0	62.2	20.2	Winter	2007
10	L3	870	310.2	67.2	20.0	Winter	2008
11	L3	870	1.283.4	77.7	23.0	Dry	2008

<sup>(1)</sup>L1, Ponta Grossa, in the state of Paraná; L2, Santo Antônio de Goiás, in the state of Goiás; and L3, Uberlândia, in the state of Minas Gerais. <sup>(2)</sup>Data from Instituto Brasileiro de Geografia e Estatística (IBGE, 2016). <sup>(3)</sup>Data from Instituto Nacional de Meteorologia (INMET, 2016). <sup>(4)</sup>Precipitation data were calculated based on the sum of the precipitation of the months of each harvest in the respective years. <sup>(5)</sup>First harvest or rainy harvest, from August to November; second harvest or dry harvest, from December to March; and third harvest or winter harvest, from April to July. RH, relative humidity.

For this classification, it was taken into account that genotypes with a relevance greater than 50%, in the set equal to 1, would present values of  $\beta_1$  statistically equal to 1 by Student's t-test. The original  $\beta_1$  values of each genotype, when subjected to the controller, were standardized. This standardization was based on the 95% confidence interval of probability based on the t-distribution, considering the null hypothesis that  $\beta_1$  is equal to 1. A value of -2 was assigned to the lower limit of the confidence interval and a value of 4, to the upper limit. The values of  $R^2$  were allocated to low and high fuzzy sets using Z-shaped (zmf) and S-shaped (smf), functions, respectively.

For the fuzzy controller, an output linguistic fuzzy variable was generated, also based on the inference system proposed by Mamdani & Assilian (1975), being called "Mamdani behavior". The obtained values were

**Table 2.** Fuzzy linguistic rules implemented in the hybrid fuzzy controller, based on the method of Eberhart & Russell and the modified method of Lin & Binns.

$P_{if}$	Input <sup>(1)</sup>			Output Behavior
	$P_{id}$	$\beta_1$	$R^2$	
Low	Low	Less than 1	Low	Poorly adapted
Low	Low	Less than 1	High	Unfavorable
Low	High	Less than 1	Low	Poorly adapted
Low	High	Less than 1	High	Poorly adapted
Low	Low	Equal to 1	Low	Poorly adapted
Low	Low	Equal to 1	High	General
Low	High	Equal to 1	Low	Poorly adapted
Low	High	Equal to 1	High	Poorly adapted
Low	Low	Greater than 1	Low	Poorly adapted
Low	Low	Greater than 1	High	Favorable
Low	High	Greater than 1	Low	Poorly adapted
Low	High	Greater than 1	High	Favorable
High	Low	Less than 1	Low	Poorly adapted
High	Low	Less than 1	High	Unfavorable
High	High	Less than 1	Low	Poorly adapted
High	High	Less than 1	High	Poorly adapted
High	Low	Equal to 1	Low	Poorly adapted
High	Low	Equal to 1	High	Unfavorable
High	High	Equal to 1	Low	Poorly adapted
High	High	Equal to 1	High	Poorly adapted
High	Low	Greater than 1	Low	Poorly adapted
High	Low	Greater than 1	High	Poorly adapted
High	High	Greater than 1	Low	Poorly adapted
High	High	Greater than 1	High	Poorly adapted

<sup>(1)</sup> $P_{if}$ , measure of the adaptability and stability of genotype behavior in favorable environments;  $P_{id}$ , measure of the adaptability and stability of genotype behavior in unfavorable environments;  $\beta_1$ , regression coefficient; and  $R^2$ , coefficient of determination.

allocated into four performance-based fuzzy sets, classifying the evaluated genotypes according to their adaptability and stability, as: general, poorly adapted, unfavorable, and favorable (Table 2). The used fuzzy linguistic rules were based on those established by Carneiro et al. (2018), in which the combination of the fuzzy sets of each variable in the linguistic fuzzy rules, based on the inference system, allowed the development of controllers capable of determining the behavior of each studied cultivar. These rules, used in the developed fuzzy controller, were based on the interpretation of the parameters of the method of Eberhart & Russell (Table 3).

The parameters estimated ( $\beta_0$ ,  $\beta_1$ , and  $R^2$ ) for the 18 common bean cultivars were subjected to the controller in order to determine the behavior of these cultivars through the obtained aggregate values (pertinence).

A hybrid fuzzy controller of the Mamdani type was also developed, based on the methods of Eberhart & Russell and Lin & Binns. It was considered hybrid because it was based on the association of the  $\beta_1$  and  $R^2$  parameters of the method of Eberhart & Russell with the values of  $P_i$  ( $P_{id}$  and  $P_{if}$ ) of the modified method of Lin & Binns.

The  $\beta_1$  and  $R^2$  parameters were transformed into input variables similar to those used in the controller of the method of Eberhart & Russell. In addition, the mean square parameters for favorable ( $P_{if}$ ) and

**Table 3.** Fuzzy linguistic rules based on the behavior of the evaluated genotypes for adaptability and stability, using the method of Eberhart & Russell adapted from Carneiro et al. (2018).

Average	Input <sup>(1)</sup>		Output Mamdani behavior
	$\beta_1$	$R^2$	
Low	Less than 1	Low	Poorly adapted
Low	Less than 1	High	Poorly adapted
Low	Equal to 1	Low	Poorly adapted
Low	Equal to 1	High	Poorly adapted
Low	Greater than 1	Low	Poorly adapted
Low	Greater than 1	High	Poorly adapted
High	Greater than 1	Low	Poorly adapted
High	Less than 1	High	Unfavorable
High	Equal to 1	Low	Poorly adapted
High	Equal to 1	High	General
High	Greater than 1	Low	Poorly adapted
High	Greater than 1	High	Favorable

<sup>(1)</sup> $\beta_1$ , regression coefficient; and  $R^2$ , coefficient of variation.

unfavorable ( $P_{id}$ ) environments were transformed into two variables similar to the mean variable of this same controller.

All data analysis was done by programming in the R software (R Core Team, 2016). The used programming algorithms are presented in Carneiro (2016).

## Results and Discussion

Based on the method of Eberhart & Russell, the cultivars with general adaptability were BRSMG Pioneiro, BRS Pontal, IAC-Carioca Tybatã, and IPR Juriti, i.e., they showed the highest values of pertinence in the general group (Table 4). This means that they met the parameters of the method to indicate an ideal cultivar, which include a high average for  $\beta_0$ , a  $\beta_1$  equal to 1, and a high  $R^2$  (Cruz et al., 2012). According to Cruz (2013), having a  $R^2$  above 80% is indicative of a greater stability. Therefore, these cultivars are capable of presenting good results both in favorable

and unfavorable environments. In this group, the IPR Juriti cultivar can be considered promising, because it obtained the highest value of pertinence.

Most cultivars – Alba, BRS 9435 Cometa, BRS Horizonte, BRSMG Majestoso, BRSMG Talismã, BRS Requite, SCS202 Guarã, IPR Colibri, IPR Saracura, FTS Magnífico, and Rubi – were classified as poorly adapted because of their lower  $\beta_0$ ,  $\beta_1$ , or  $R^2$ . However, the Campeão, Pérola, and BRS Estilo cultivars presented specific adaptability to favorable environments, falling into the favorable group due to their high average  $\beta_0$  and  $\beta_1 > 1$ . In addition, these cultivars had a  $R^2$  greater than 80%, which is indicative of a high predictability (stability), and, therefore, are recommended when the goal is to increase productivity by improving the environment, especially of crops grown by large farmers using a high technological level.

Although the controller, based on the method of Eberhart & Russell, did not identify cultivars with adaptability to unfavorable environments, IPR

**Table 4.** Input variables and classification of the behavior of 18 common bean (*Phaseolus vulgaris*) cultivars subjected to the fuzzy controller based on the method of Eberhart & Russell<sup>(1)</sup>.

Cultivar	Input <sup>(1)</sup>			Pertinence of behavior (%) <sup>(2)</sup>			
	$\beta_0$ (kg ha <sup>-1</sup> )	$\beta_1$	$R^2$ (%)	GE	PA	FAV	UNF
Alba	1,756	1.03 <sup>ns</sup>	0.88	21	79	3	0
BRS 9435 Cometa	1,811	0.99 <sup>ns</sup>	0.95	31	69	0	0
BRS Estilo	2,102	1.13*	0.95	44	13	56	0
BRS Horizonte	1,752	0.84*	0.82	21	62	0	21
BRSMG Majestoso	1,880	0.99 <sup>ns</sup>	0.89	45	55	0	0
BRSMG Pioneiro	2,016	0.95 <sup>ns</sup>	0.84	71	29	0	6
BRSMG Talismã	1,851	1.05 <sup>ns</sup>	0.97	39	61	7	0
BRS Pontal	2,112	1.11 <sup>ns</sup>	0.96	62	12	38	0
BRS Requite	1,835	0.88 <sup>ns</sup>	0.78	35	59	0	35
Campeão	2,079	1.17*	0.93	24	16	76	0
SCS202 Guarã	2,012	0.97 <sup>ns</sup>	0.70	15	73	0	1
IAC-Carioca Tybatã	1,934	1.06 <sup>ns</sup>	0.97	58	42	13	0
IPR Colibri	1,719	0.84*	0.85	16	66	0	16
IPR Juriti	2,017	1.01 <sup>ns</sup>	0.96	74	26	1	0
IPR Saracura	1,875	0.81**	0.94	19	56	0	44
FTS Magnífico	1,640	0.76**	0.90	3	89	0	7
Pérola	1,969	1.26**	0.96	0	35	65	0
Rubi	1,858	1.05 <sup>ns</sup>	0.88	40	60	10	0

<sup>(1)</sup> $\beta_0$ , mean;  $\beta_1$ , regression coefficient; and  $R^2$ , coefficient of determination. <sup>(2)</sup>GE, general behavior; PA, poorly adapted; FAV, favorable; and UNF, unfavorable. \* and \*\*Significant by the t-test, at 5 and 1% probability, respectively, for the angular coefficient when assuming the null hypothesis  $\beta_1=1$ . <sup>ns</sup>Nonsignificant, at 5% probability.

Saracura presented the highest value of pertinence in the group classified as having unfavorable behavior, which can be explained by its low  $\beta_1$  estimate. Therefore, this cultivar is the most suitable for unfavorable environments. This is important information, as it shows that the fuzzy methodology, not only allows to classify, but also to identify better genotypes by the magnitude of pertinence, as evidenced by Carneiro et al. (2018).

The fuzzy hybrid controller, based on the method of Eberhart & Russell and Lin & Binns (Table 5), classified the BRSMG Pioneiro, BRS Pontal, IAC-Carioca Tybatã, and IPR Juriti cultivars as of general adaptability due to their low  $P_{if}$  and  $P_{id}$ , high average  $\beta_0$  above the general average of 1.952 kg ha<sup>-1</sup>,  $\beta_1=1$ , and elevated  $R^2$ . In the method of Lin & Binns, genotypes with lower  $P_{if}$  and  $P_{id}$  values, respectively, are considered ideal for favorable and unfavorable environments. Therefore, these cultivars can be recommended for both of these environments, i.e., for small- and large-scale farming with a low and high technological level, respectively (Cruz et al., 2012). The IPR Juriti cultivar

stood out for presenting the highest value of pertinence within this group.

The Campeão, Pérola, and BRS Estilo cultivars showed the highest values of pertinence in the group classified as favorable, with adaptability to favorable environments. This is due to their low  $P_{if}$ , high average  $\beta_0$  above the general average of 1.952 kg ha<sup>-1</sup>, and  $\beta_1>1$  (Table 5).

Both the controller based on Eberhart & Russell and the hybrid controller based on Eberhart & Russell and Lin & Binns identified the same cultivars with a similar significant behavior. However, there was a difference in the classification of the cultivars for unfavorable environments, since only the hybrid controller identified a cultivar – IPR Saracura – as being adapted to these environments due to its low  $P_{id}$  and  $\beta_1<1$ ; therefore, this genotype is recommended for small farmers with few technological resources. These results show that, although the two used controllers are able to classify all cultivars according to the criteria of each method, the hybrid controller, based on the methods of Eberhart & Russell and Lin & Binns, was

**Table 5.** Input variables and classification of the behavior of 18 common bean (*Phaseolus vulgaris*) cultivars subjected to the fuzzy hybrid controller based on the method of Eberhart & Russell and the modified method of Lin & Binns<sup>(1)</sup>.

Cultivar	Input <sup>(1)</sup>				Pertinence of behavior (%) <sup>(2)</sup>			
	$P_{if}$	$P_{id}$	$\beta_1$	$R^2$ (%)	GE	PA	FAV	UNF
Alba	496371	178036	1.03 <sup>ns</sup>	0.88	12	71	3	12
BRS 9435 Cometa	366225	149359	0.99 <sup>ns</sup>	0.95	26	52	0	26
BRS Estilo	132061	76490	1.13*	0.95	44	22	56	20
BRS Horizonte	498622	166280	0.84*	0.82	17	62	0	17
BRSMG Majestoso	340630	123456	0.99 <sup>ns</sup>	0.89	45	52	0	45
BRSMG Pioneiro	202048	97971	0.95 <sup>ns</sup>	0.84	65	35	0	28
BRSMG Talismã	263076	151438	1.05 <sup>ns</sup>	0.97	25	64	7	25
BRS Pontal	114641	59214	1.11 <sup>ns</sup>	0.96	62	18	38	18
BRS Requite	660903	85544	0.88 <sup>ns</sup>	0.78	12	59	0	41
Campeão	147445	62257	1.17*	0.93	24	21	76	21
SCS202 Guarã	399347	93933	0.97 <sup>ns</sup>	0.70	15	57	0	15
IAC-Carioca Tybatã	239278	10093	1.06 <sup>ns</sup>	0.97	63	37	13	33
IPR Colibri	695089	133407	0.84*	0.85	9	63	0	37
IPR Juriti	166268	70809	1.01 <sup>ns</sup>	0.96	77	19	1	23
IPR Saracura	393800	88380	0.81 <sup>ns</sup>	0.94	19	29	0	56
FTS Magnifico	759300	145918	0.76**	0.90	3	72	0	28
Pérola	194102	146841	1.26**	0.96	0	27	72	0
Rubi	315347	172779	1.05 <sup>ns</sup>	0.88	14	56	10	14

<sup>(1)</sup> $P_{if}$ , measure of the adaptability and stability of genotype behavior in favorable environments;  $P_{id}$ , measure of the adaptability and stability of genotype behavior in unfavorable environments;  $\beta_1$ , regression coefficient; and  $R^2$ , coefficient of determination. <sup>(2)</sup>GE, general behavior; PA, poorly adapted; FAV, favorable; and UNF, unfavorable. \*and \*\*Significant by the t-test, at the 5 and 1% probability, respectively, for the angular coefficient when assuming the null hypothesis  $\beta_1=1$ . <sup>ns</sup>Nonsignificant, at 5% probability.

more complete. This may be explained by the fact that the association of these two methods results in a higher number of classification parameters and, consequently, in a greater discrimination power.

Therefore, the selection of common bean cultivars by fuzzy logic using both the methods of Eberhart & Russell and Lin & Binns is recommended due to the different principles applied and complementary information, which make it possible to effectively and safely identify the response of genotypes to environmental changes. This is an advantage in comparison with the work of Carneiro et al. (2018), which only considered the method of Eberhart & Russell. The complementarity of those two methods was also evidenced by Nascimento et al. (2013) and Vasconcelos et al. (2015). However, these studies showed that there is a low correlation between the methods of Eberhart & Russell and Lin & Binns, indicating that using the method of Eberhart & Russell, together with a nonparametric method, can provide complementary information about the phenotypic stability of the assessed cultivars.

Both the controller based on Eberhart & Russell and the hybrid controller based on Eberhart & Russell and Lin & Binns were able to classify the cultivars as an experienced researcher would have when considering the obtained parameters. Carneiro et al. (2018) found similar results using fuzzy controllers to classify common bean genotypes for adaptability and stability, taking into account grain yield data. The correct classification by fuzzy controllers is due to the composition of input and output linguistic variables, which allow the experience of the operator to be codified in rules that can be used by the computer to interpret and provide accurate and useful information for decision-making (Simões & Shaw, 2007). Therefore, fuzzy logic has a powerful ability to model the complex human logic (Türksen, 2007), making it superior to the other more classical statistical methodologies used in decision-making (Piterbarg, 2011; Viertl, 2011; Blanco-Fernández et al., 2013).

Besides allowing the classification of a genotype into a group, fuzzy controllers also show the pertinence of the genotypes to compose other groups. For example, the BRS Estilo cultivar was classified as suitable for a favorable environment (pertinence of 56), but also had a high pertinence (44) for the general behavior

group (Table 5). This additional information is useful, according to Kuo et al. (2009), for the systematization of imprecise knowledge, which is important for genetic improvement. Even though no cultivars were recommended for unfavorable environments when considering only the Eberhart & Russell method (Table 4), fuzzy logic showed that BRS Horizonte, BRS Requite, and IPR Saracura had a high pertinence for this group. This indicates that these genotypes could be used as parents in breeding programs to obtain suitable genotypes for an unfavorable environment.

The results of the present study are indicative that the controller based on Eberhart & Russell and the hybrid controller based on Eberhart & Russell and Lin & Binns were useful and efficient to aid in the process of cultivar recommendation, based on established fuzzy rules. Therefore, this technique becomes a great ally to breeding programs because of its simplicity and automation capacity, especially when there is a large number of evaluated genotypes.

## Conclusions

1. The BRSMG Pioneiro, BRS Pontal, IAC-Carioca Tybatã, and IPR Juriti common bean (*Phaseolus vulgaris*) cultivars present general adaptability, whereas Campeão, Pérola, and BRS Estilo show specific adaptability to favorable environments, and IPR Saracura is adapted to unfavorable environments.
2. Both the fuzzy controller based on Eberhart & Russell and the hybrid controller based on Eberhart & Russell and Lin & Binns classify all cultivars correctly according to the estimated statistical parameters.
3. Fuzzy logic can be used to automate the classification of genotypes for adaptability and stability, which can reduce the unnecessary expenditure of time and human resources for breeding programs.

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