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Fuzzy logic discriminant function for evaluating goats exposed to verminosis occurrence regarding resistance, resilience, or sensitivity to parasitism

Função discriminatória de lógica ***Fuzzy*** para avaliação de cabras expostas a ocorrência de verminose quanto à resistência, resiliência ou sensibilidade ao parasitismo

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Abstract
Worm infections pose a significant challenge to goat farming in the tropics. While individual variations in the animals' response to this disease are observed, understanding its genetic component is crucial for establishing effective herd production management, prioritizing the selection of goats with higher resistance to parasitism. This study aimed to assess goat response to worm infection under natural field conditions using data on eggs per gram of feces (EPG), body condition score (BCS), and conjunctival mucosa coloration (FAMACHA©). Cluster analysis and artificial intelligence (AI) techniques were applied to 3,839 data points from 200 individuals in an experimental goat herd in Piauí, Brazil. The study considered the phenotypic expression of resistance, sensitivity, and resilience to worm infection as responses to parasitism. Three clustering methods, namely Ward, Average, and k-means, were employed and compared with fuzzy logic obtained through the CAPRIOVI web software. The analysis revealed statistically significant differences (P<0.05) between the groups of animals classified as resistant, resilient, and sensitive to parasitism. Pregnancy and peripartum were identified as stages of heightened sensitivity to parasitism (P<0.05). Among the clustering techniques, traditional statistical methods exhibited excellent performance, with an overall accuracy percentage exceeding 90.00%. In contrast, CAPRIOVI's fuzzy logic demonstrated lower overall accuracy (77.00%). The clustering methods showed similar efficiency, but differed in terms of the distribution of animals per group, with a tendency towards greater numbers in the resistant category. Fuzzy logic circumvented this limitation by enabling the formation of groups tailored to meet the producer's interests, adding consistency in terms of the animals' response to worm infection. This finding highlights the potential of the software for goat health management.
Keywords: artificial intelligence; body condition; discriminant analysis; FAMACHA©

Resumo
A incidência de verminose é um dos principais obstáculos para a caprinocultura nos trópicos. A variação individual da resposta do animal à enfermidade existe, mas precisa ser determinado o seu componente genético e estabelecer o manejo zootécnico dos rebanhos, priorizando a seleção de animais mais resistente ao parasitismo. Objetivou-se nesse estudo avaliar a resposta de cabras à incidência de verminose sob condições de infecção natural a campo, com informações de ovos por grama de fezes (OPG), escore da condição corporal (ECC) e grau de coloração da mucosa conjuntiva (FAMACHA©), recorrendo a utilização de análise de agrupamento e a aplicação de inteligência artificial (IA). Foram utilizadas 3.839 informações de 200 indivíduos em um rebanho experimental de caprinos no Piauí. Considerou-se como resposta ao parasitismo a expressão fenotípica de resistência, sensibilidade e resiliência a verminose, submetidos a três métodos de agrupamento: Ward, Average e K-means, comparado com a lógica *Fuzzy*, obtidos com o software web CAPRIOVI. Os resultados demonstraram que os grupos de animais resistente, resiliente e sensível ao parasitismo foram estatisticamente distintos (P<0,05). As cabras durante a gestação e o periparto foram identificadas como fases de maior sensibilidade ao parasitismo (P<0,05). O CAPRIOVI aplica a lógica *Fuzzy* e apresentou o menor percentual de acerto global (77,00%), enquanto os métodos estatísticos tradicionais se destacaram com percentual de acerto global superior a 90,00%, demonstrando excelência estatística com esse fim. Os métodos de agrupamentos apresentaram semelhança na eficiência, mas diferiram quanto à distribuição de animais por agrupamento, com tendência de maior quantidade na categoria resistente. A aplicação da lógica *Fuzzy* contornou essa limitação ao direcionar a formação dos grupos visando atender o interesse do produtor, inserindo consistência em termos de resposta dos animais a verminose, qualificando o software com potencial para adequação ao manejo sanitário de caprinos.
Palavras-chave: análise descriminante; condição corporal; FAMACHA©; inteligência artificial

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1. Introduction

Gastrointestinal parasitism has long been recognized as a significant constraint on goat production, negatively impacting herd productivity [1, 2]. While not a recent issue, it remains an ever-contemporary problem that has been addressed through various strategies, with certain points of consensus existing between them. In tropical environments, ecosystems favorable for parasite development prevail, and goat hosts employ two main strategies to combat the adverse consequences of parasitism: resistance and tolerance.

Broad-spectrum drug application is the primary method for controlling parasitism, but it has contributed to anthelmintic resistance and the need for integrated control practices [3]. Unfortunately, vermifuge use does not reduce parasite prevalence and creates the need for alternative parasite control strategies to minimize health risks arising from the increased concentration of drug residues in meat [4] and in the environment [5].

Advances in scientific knowledge in recent decades have emphasized the importance of molecular marker-assisted selection to enhance individual genetic resistance response [6]. In Brazil, Santos et al. [7] identified genes associated with resistance to worm infection, while Rodrigues et al. [8] used Bayesian statistics with an animal model to estimate genetic parameters related to worm infection resistance.

The most common measure used to study resistance to gastrointestinal nematode infections is the egg count per gram of feces (EPG) test, a simple and useful technique for monitoring herd parasitism levels [8]. However, the incorporation of EPG as a routine in herd health management may face challenges. Therefore, the use of other health-associated traits becomes more appropriate to achieve greater efficiency in identifying resistance to worm infection.

Body condition scores are useful for detecting weight loss situations associated with changes in the animal's parasitic load [9, 10]. The FAMACHA© method is a selective criterion that has been used to control worm infections, as it is a practical, fast, and inexpensive approach. By comparing shades of conjunctival mucous membranes, it indicates the degree of anemia in animals, allowing the identification of those with potential resistance or resilience to parasitism [10].

Since the worm infection response phenotype involves three measurable traits (EPG, body condition score (BCS), and FAMACHA©), identifying the best methodology for characterizing resistant animals is essential. Cluster analysis has proven useful in grouping animals based on specific criteria. Based on the partitioning criterion, clustering methods are categorized as hierarchical, where the default algorithm involves constructing a dendrogram; or non-hierarchical, with the most common method being k-means.

Araújo et al. [11] conducted similar studies in sheep using non-hierarchical clustering with the k-means algorithm, considering EPG, FAMACHA©, BCS, and hematocrit to form resistant, resilient, and sensitive groups. In a similar context, Bitar et al. [12] used fuzzy logic to estimate parameters of the relationship between weight and length, considering uncertainties inherent to the model. They found that non-parametric processes provided more consistent estimates, and fuzzy logic allowed parameter estimation directly from the centers of the groups formed by k-means cluster analysis. Notably, the researchers considered the most prominent finding in the study to be the intervals obtained with the fuzzy inference system.

Furthermore, Castro et al. [13] applied fuzzy logic as an artificial intelligence mechanism in managing small ruminant herds due to its agile computational capacity, enabling field use and individual health status classification. They highlighted the scarcity of studies incorporating automation in the production process of these animal species.

Therefore, this study aims to evaluate the phenotypic response to worm infection in female goats under natural field infection conditions, utilizing data from EPG, BCS, and FAMACHA© collected from the Anglo-Nubian breed database of an experimental herd. The study employed cluster analysis and artificial intelligence techniques for analysis.

2. Material and methods

2.1 Ethics in animal experimentation

All experimental procedures involving goats were approved by the Ethics Committee on Animal Use (CEUA) of the Federal University of Piauí, Brazil (approval no. 0423/2017).

2.2 Database

The study utilized a dataset consisting of 3,839 records collected from 200 individuals within the Anglo-Nubian goat database of the experimental herd at the Department of Animal Science, Federal University of Piauí, Brazil. The data covered the period from 2009 to 2019 and included information on EPG, BCS, and FAMACHA© scores. The goats were managed under a semi-intensive system and exposed to grazing contamination. To characterize the profile of the database and justify the suitability of the herd for this study, the following points are presented:

From 2001 to 2017, we sought to expand the phenotypic variability in the response to worm infection in the herd. For this purpose, we also intentionally incorporated females with a high EPG value (sensitivity profile). However, this approach led to an increase in goat mortality, as observed in a previous study by Lima et al. [14]. To mitigate this, starting in 2005, all females were administered a vermifuge in the first week after giving birth. This strategy aimed to preserve a large number of animals with a resistance profile against worm infection within the herd.

The reproductive management approach included at least one breeding season per semester, ensuring that groups of animals were at the same physiological stage during both the first and second semesters. Because data collection occurred throughout the year, the database contains information on pregnant and non-pregnant goats that were simultaneously exposed to parasitism.

The goats were managed on cultivated grass paddocks throughout the year. During the rainy season, goats with the same physiological condition were placed together in the same pasture due to varying sensitivity levels depending on the physiological condition during data collection. Previous studies conducted over the last 20 years with data from the same herd confirmed that the goats were exposed to parasites year-round [14].

Sanitary management during the analyzed period was based on the EPG value, with an average of three collections per semester. The vermifuge was applied when 10% of the goats had EPG values greater than 1000, following the recommendations by Costa et al. [15]. Fecal collections for EPG counts occurred at least six times a year, with intervals always greater than 40 days between collections in each semester from 2009 to 2019. Additionally, on the same dates, FAMACHA© scores and BCS values were recorded for all reproductive-age females. The data were edited to consider information from the second and third orders of kidding.

EPG values were obtained at the animal health laboratory (LASAN-UFPI) using samples of feces collected directly from the animals' rectal ampulla, following the technique by Gordon and Whitlock [16]. To minimize evaluator bias, the average of scores attributed by three evaluators was considered for obtaining BCS and FAMACHA© values. One evaluator was consistently used in successive evaluations.

FAMACHA© scores were obtained by assessing the coloration of the ocular conjunctiva mucosa using a guide card developed for field use. Scores ranged from 1 to 5, with 1 representing animals without anemia and 5 indicating animals with high levels of anemia. Body condition score was assessed also based on a scale of 1 to 5, following the methodology used by Osório [17], which involved visual assessment and palpation in the lumbar region to locate the spinous and transverse processes. The scoring process considered the detection of fat and muscle deposition, with 1 corresponding to a very thin animal and 5 to an animal showing signs of obesity.

2.3 Worm resistance (WR) and fuzzy logic

This study investigates the integration of automation into health management, specifically in anthelmintic treatment, to facilitate decision-making regarding resistance to parasitism caused by worm infections. To achieve this, a discriminatory function based on fuzzy logic was explored as an alternative approach. The analysis utilized CAPRIOVI software (https://easii.ufpi.br/capriovi), a web-based system designed for farm management, which includes a module assisting goat and sheep breeders in diagnosing the need for anthelmintic treatment based on feces collection data throughout the year.

The mechanism operates on computational intelligence, where input involves entering values of relevant traits related to the animals' response to worm infections and the output is a classification of animals based on their need for deworming treatment [18].

In this study, data from 3,839 animals were used, including EPG, FAMACHA© scores, and BCS values. CAPRIOVI utilized a discriminatory function with fuzzy logic to estimate a score for each animal's trait called "WR" (worm resistance), ranging from 1 to 10. A higher WR score indicates greater resistance to gastrointestinal nematodes. The calculation of WR does not require scale transformation of EPG values. Consequently, based on the WR trait, animals were categorized as resistant (score > 7), resilient (score between 4 and 7), or sensitive (score < 4), respectively.

2.4 Statistical analysis

The primary focus was on evaluating goats' response to worm infection, considering resistance, resilience, and sensitivity. Artificial intelligence (AI) was employed using a function with fuzzy logic available in the CAPRIOVI web software to determine the phenotypic expression responses to worm infection. The same dataset underwent cluster analysis using three multivariate methods: Ward, Average (hierarchical), and k-means (non-hierarchical). The predetermined objective was to form three distinct groups in each method, representing animals with the profiles considered Resistant, Resilient, and Sensitive, based on the previous classification method.

The Euclidean distance matrix was employed to quantify the dissimilarity between pairs of elements (and). This measure was obtained by calculating the square root of the sum of squared differences between the values of and ($v = 1,2,\ldots, p$):

$$d(x_i, x_j) = \sqrt{\sum_{v=1}^{p} (x_{iv}, x_{jv})^2}$$

Using estimates of Euclidean distances between the individuals derived from standardized data, we conducted cluster analysis through hierarchical techniques employing the Ward and Average algorithms. Additionally, k-means dendrograms were visually inspected. To gauge the effectiveness of these methods, discriminant analysis was employed, and its performance was compared with fuzzy logic. In other words, with the prior definition of three groups to be formed, the percentage of coincidence of the discriminant function was utilized as a metric to evaluate the efficacy of each method.

Subsequently, a descriptive analysis categorized goats into groups based on resistance, sensitivity, and resilience. Resistance was characterized by lower mean EPG and FAMACHA© scores, coupled with a higher BCS. Conversely, sensitivity was indicated by the opposite characteristics. Intermediate EPG values along with good body condition denoted resilience, in line with previous studies [11].

The results were subjected to the same discriminant function ($p<0.05$) to define the statistical quality of the formed groups (degree of coincidence) and assess the quality of AI utilization compared to clustering methods in determining animal responses to worm infection. Accuracy, as defined by the discriminant function, guided this assessment. Further, multivariate and univariate analyses were conducted on the results.

In multivariate analysis (Manova), the EPG, BCS, and FAMACHA© traits were considered. By comparing the multivariate means, the clustering methods were concurrently evaluated for their ability to discriminate animals as Resistant, Resilient, or Sensitive to endoparasitism. Each clustering method underwent univariate analysis, adopting Resistant, Resilient, and Sensitive as distinct treatments. Tukey's test ($P<0.05$) was applied, and the influence of goat physiological stage and age on data collection day, treated as fixed effects, was examined. All statistical analyses were executed using R software [19].

3. Results and discussion

This study focused on evaluating the response of goats to gastrointestinal endoparasite infection, specifically analyzing EPG, BCS, and FAMACHA© data from females only. The advantage of utilizing these traits together stems from their positive and negative correlations with worm resistance, as highlighted in previous research [8]. These traits have been consistently linked to animals' reactions to worm infections, with the aim of achieving higher scores and lower EPG and FAMACHA© values [11, 6]. This alignment is crucial when applying functions involving fuzzy logic, a methodology employed in this study.

By amalgamating the three traits (EPG, BCS, and FAMACHA©) into a composite termed worm resistance (WR), which encompasses values ranging from 1 to 10, the software generated the subsequent classifications: a) Treatment recommended for the animals; b) No treatment, but close observation advised; and c) No treatment required. Statistical analysis revealed significant differences ($P<0.05$) between the three groups of animals—resistant, resilient, and sensitive to parasitism. The corresponding means are presented in Table 1, showcasing values of 2.47 (Sensitive), 4.87 (Resilient), and 7.31 (Resistant).

Table 1. Means of the WR, EPG, BCS, and FAMACHA© traits across different physiological stages in Anglo-Nubian goats phenotypically classified as resistant, resilient, or sensitive to field-based worm parasitism in a research-intended herd

Group[1] Physiological stage[2]	WR	EPG	BCS	FAMACHA©
Resistant[1]	**7.31[A]**	**222[A]**	**3.13[A]**	**2.35[A]**
Pregnancy	7.33[a]	202[a]	3.19[a]	2.64[a]
Lactation	7.33[a]	222[a]	3.12[a]	2.55[a]
Peripartum	7.29[a]	251[a]	3.15[a]	2.64[a]
Non-pregnant	7.27[a]	211[a]	3.09[a]	2.46[a]
Resilient[1]	**4.87[B]**	**612[B]**	**2.53[B]**	**3.18[B]**
Pregnancy	5.16[ab]	697[b]	2.66[a]	3.26[b]
Lactation	5.06[ab]	535[ab]	2.42[b]	3.23[ab]
Peripartum	4.99[b]	710[b]	2.53[ab]	3.11[a]
Non-pregnant	5.25[a]	507[a]	2.51[ab]	3.10[a]
Sensitive[1]	**2.47[C]**	**1945[C]**	**2.05[C]**	**3.93[C]**
Pregnancy	2.62[a]	1.561[a]	2.15[a]	3.89[a]
Lactation	2.39[a]	2.162[b]	1.96[a]	4.00[a]
Peripartum	2.40[a]	2.325[b]	2.06[a]	3.87[a]
Non-pregnant	2.46[a]	1.732[a]	2.04[a]	3.94[a]

[1] Means with common uppercase letters in the column indicate that the groups of animals do not differ ($P<0.05$) by Tukey's test, in their response to parasitism. [2] Means in the physiological stages with common lowercase letters in the column do not differ ($P<0.05$) by Tukey's test within groups. WR = worm resistance; EPG = eggs per gram of feces; BCS = body condition score; FAMACHA© = color of the conjunctival mucosa.

The observed means of EPG, FAMACHA©, and BCS (as detailed in Table 1) exhibit significant statistical differences ($P<0.05$) in univariate analysis, thereby validating the classification of animals into the resistant, resilient, and sensitive groups, which aligns with the analysis of the WR trait. As depicted in Table 1, among the group of resistant animals, physiological condition seems to exert no influence on the response to parasitism ($P>0.05$). Conversely, the response of animals classified as sensitive appears to be heavily contingent on their physiological state. The highest sensitivity is particularly prominent during the pregnancy and peripartum stages, with notable effects discerned across all four traits ($P<0.05$). In the case of resilient animals, the behavior seems substantially attributed to measurements taken from non-pregnant goats, indicating a prevailing tendency towards resistance to worm infection under this physiological condition.

Although all females underwent deworming after each parturition, the impact of this practice on the results is expected to be minimal. This is because data collection preceded deworming, allowing for a sufficient 40-day interval (between deworming and collection) during which recontamination could occur. Any potential influence on the groups appears to stem from varying resistance levels exhibited by the animals. It is pertinent to note that the results presented in Table 1 stem from goats that were continuously exposed to worm presence throughout the analyzed year. This assertion is founded on the data under study as well as a review of literature from the past 20 years, where data from the same herd were employed.

The presence of hematophagous endoparasites, as described by Lima et al. [14], was an outcome of grazing practices in an irrigated area during the dry season—a management strategy known to foster their occurrence. This observation resonates with findings by Costa Júnior et al. [20] and Batista et al. [21], which strongly highlight the prevalence of *H. contortus* under such conditions. These two studies bolster the inclusion of this herd's dataset, as it provides crucial insights for guiding the utilization of irrigated pastures in goat rearing in the region.

Given the established understanding that higher EPG values denote sensitivity to parasitism, lower values signify resistance, and intermediate values characterize resilience (indicating an animal's ability to sustain production despite parasitization, or an indication of tolerance to parasitism [10, 22]), it is plausible to affirm that the WR trait remains consistently variable and aptly characterizes the three response levels among the evaluated goats. This uniformity is similarly observed across the other three analyzed traits, thus serving as a testament to the software's suitability for goat health management.

Thus, several noteworthy points arise that are pertinent to evaluating the effectiveness of fuzzy logic employed in this study: a) Fluctuations in weight can serve as a valuable indicator for identifying animals exhibiting the desired resistance profile against worm infections within herds. In this context, Hayward et al. [10] suggest that the inverse relationship between parasite load and body weight could stem from parasite-induced anorexia as well as intestinal wall damage leading to clinical diarrhea and reduced protein absorption. b) Resistant goats exhibit greater stability in relation to physiological influences (P<0.05), displaying functional steadiness with minimal fluctuations in body condition or less susceptibility of BCS variation to parasitic influence (P>0.05), contrasting with animals displaying sensitivity or resilience (Table 1); and c) Pregnancy and peripartum phases emerge as periods of heightened susceptibility to parasitism (Table 1).

Table 2 exhibits the multivariate means of traits including eggs per gram of feces (EPG), body condition score (BCS), and conjunctival mucosa color (FAMACHA©), within groups of goats categorized as Resistant, Resilient, and Sensitive to worm infection. The categorization was established through a discriminatory function based on fuzzy logic, and the multivariate means of groups were estimated using the Ward, Average, and k-means clustering methods.

Table 2. Multivariate means of the EPG, BCS, and FAMACHA© traits of groups of Anglo-Nubian goats classified as resistant, resilient, or sensitive to parasitism by worms, by multivariate clustering methods

Method	Classification	Trait[1]		
		EPG	BCS	FAMACHA©
Fuzzy logic	Resistant	270[a]	3.22[c]	2.95[a]
	Resilient	637[b]	2.58[b]	3.33[b]
	Sensitive	1.657[c]	2.12[a]	3.83[c]
Ward	Resistant	362 [a]	2.61[c]	3.29[a]
	Resilient	1254[b]	2.42[b]	3.59[b]
	Sensitive	3228 [c]	2.27[a]	3.86[c]
Average	Resistant	638[a]	2.56[c]	3.38[a]
	Resilient	2407[b]	2.25[b]	3.78[b]
	Sensitive	4610[c]	1.91[a]	4.15[c]
K-means	Resistant	436[a]	2.62[c]	3.32[a]
	Resilient	1431[b]	2.31[b]	3.65[b]
	Sensitive	3228[c]	2.27[a]	3.84[c]

[1]Significant difference at 5% between all mean vectors of the clusters at 5%, by MANOVANP with the Adonis function from the Vegan package. EPG = eggs per gram of feces; BCS = body condition score; FAMACHA© = color of the conjunctival mucosa.

Notably, all three clustering methods exhibited similar outcomes to those derived from AI, collectively detecting multivariate significance across the three traits analyzed within groups identified as Resistant, Resilient, or Sensitive to worm infection. Resistant animals displayed concurrently lower EPG, reduced FAMACHA© scores, and higher BCS, while sensitive animals exhibited the opposite trends. These findings align with prior research indicating that goats/sheep classified as resistant generally manifest lower EPG and FAMACHA© values in comparison to sensitive counterparts [8, 23].

These results are in line with those made by Araújo et al. (11), who employed the k-means algorithm in a study involving Santa Inês breed sheep. Within this study, animals classified as sensitive exhibited evident clinical signs of anemia, as indicated by elevated FAMACHA© scores. This correlation can be attributed to the prevalence of *H. contortus*, a prominent endoparasite within the herd[20, 21].

Statistical analysis confirmed significant divergence in the vector of multivariate means (P<0.05). Specifically, animals classified as sensitive displayed EPG values 4.5 times greater than their resistant counterparts (Table 3). This trend aligns with results observed by Coutinho et al. [25] in goats, where such disparities were attributed to genetic and host-related factors including age and physiological state, all of which contribute to differing responses between animals of distinct breeds or even within the same breed.

From a statistical standpoint, the use of multivariate analysis (comprising EPG, FAMACHA©, and BCS) reveals a comparable performance between the three clustering methods and AI in segregating animals into the three response-based groups of "Resistant," "Resilient," or "Sensitive" to parasitism. However, it's noteworthy that the clustering methods do exert an influence on trait means (P<0.05).

Considering the example of the group classified as resistant by fuzzy logic and the Average clustering method (Table 2), the mean EPG differed substantially, measuring 270 and 638 respectively—a variation exceeding 200%. This pattern is similarly observed within the other two groups, those deemed sensitive and resilient.

The results obtained using AI and fuzzy logic demonstrated mean EPG values for the "Resistant," "Resilient," and "Sensitive" phenotype groups that align with literature recommendations. The EPG means remain within the range reported by Idika et al. [26]. Additionally, FAMACHA© and BCS means fall within expected normal values for these traits [8, 27]. Conversely, multivariate clustering methods tend to elevate these means due to a greater prevalence of animals with profiles of resistance against worm infection.

Table 3 shows the outcomes of discriminant function analysis with regard to accuracy rate (efficiency), comparing the use of AI and clustering methods for classifying Anglo-Nubian goats as Resistant, Resilient, or Sensitive to worm infection, based on EPG, BCS, and FAMACHA©.

Table 3. Measurement of the efficiency of clustering methods and AI, by discriminant function, to distribute Anglo-Nubian goats into three groups: Resistant, Resilient, and Sensitive to parasitism based on based on EPG, BCS, and FAMACHA©

Method	Classification	n	Classification, in n			Accuracy (%)	Overall accuracy (%)
			Resistant	Resilient	Sensitive		
Fuzzy logic	Resistant	29	17	12	0	58.62	77.00
	Resilient	101	5	88	8	87.13	
	Sensitive	70	0	21	49	70.00	
Ward D clustering	Resistant	110	86	16	0	77.78	92.00
	Resilient	72	0	72	0	100	
	Sensitive	18	0	0	18	100	
Average clustering	Resistant	172	172	0	0	100	100
	Resilient	23	0	23	0	100	
	Sensitive	5	0	0	5	100	
K-means clustering	Resistant	131	131	0	0	100	96.00
	Resilient	51	7	44	0	86.27	
	Sensitive	18	0	1	17	94.40	

n = number of animals.

It is noteworthy that irrespective of the method employed, no animal classified as resistant was simultaneously labeled as sensitive, or vice versa. Additionally, the descending order of overall accuracy using the employed clustering methods was: Average (100%), k-Means (96%), and Ward (92%).

Nonetheless, discriminant analysis revealed a trend of a difference in the number of animals that were allocated to each group. Particularly, a stark disparity exists in the number of animals categorized as resistant, reaching 86% within the Average method, whereas the sensitive group comprises a mere 2.5%. Hence, it appears that the statistical optimality initially observed might not entirely align with the animal-performance optimality concerning the suitability of the clustering method for the objectives of this specific study nature.

Clustering algorithms do not inherently dictate the number of groups to be formed. This characteristic can complicate result interpretation; i.e., the use of multivariate methods faces limitations from a practical point of view as in livestock decision-making, as is the case in this study. However, in the context of this research, the determination of group number was straightforward due to a known prior division into three groups. Consequently, it seems plausible that this pre-defined tripartite division influenced the outcomes of the evaluated multivariate clustering methods.

Regarding the utilization of fuzzy logic in discriminant analysis, the outcomes were as follows: 29 animals (4.5%) categorized as resistant, 101 animals (50.5%) as resilient, and 70 animals (35%) as sensitive. In contrast, the Average grouping method classified 86% of animals as resistant, 11.5% as resilient, and 2.5% as sensitive. A comparison with Figure 1 suggests that the Average method did not distinctly differentiate between the groups. Comparing these outcomes to the k-means method, which predominantly labeled 96% of animals as resistant, it appears that distinguishing between resistant and resilient animals, with overlapping dispersion, proved challenging for the algorithm, as depicted in Figure 1.

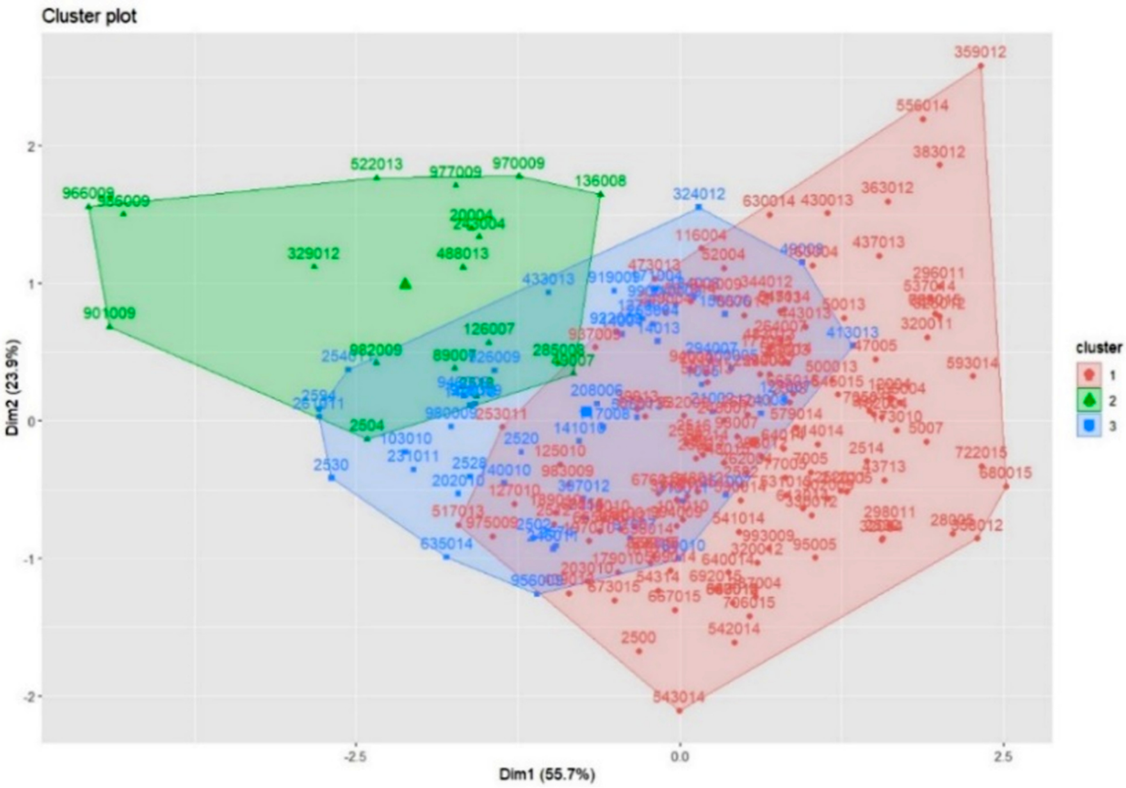

Figure 1. Dispersion resulting from cluster analysis obtained with the k-means algorithm (1 – Resistant; 2 – Sensitive; 3 – Resilient).

It is essential to acknowledge that this outcome does not indicate a statistical limitation of the grouping ability of the method. Rather, it suggests a mismatch between the method and the objectives of the study. In this scenario, where classifying animals as resistant, resilient, or sensitive suffices, the method might not be optimally suited.

Table 3 depicts the efficiency of animal allocation across groups using the same discriminant function. Fuzzy logic-based discriminant analysis demonstrated the lowest overall accuracy (77.00%), while the Average clustering method displayed the highest coincidence rate (100%) in animal discrimination. In the context of livestock classification, the ascending order of animals showing resilience, sensitivity, and resistance, as revealed by the logic-based discrimination function, aligns with existing literature [13]. Notably, this order did not manifest when utilizing traditional clustering methods, which yielded more animals with a resistance profile against parasitism in herds.

It is important to note that considering one goat more resistant than another does not discount the possibility of temporary sensitivity differences. These variations could reflect seasonal parasite load peaks, which are lower in resistant animals. Fuzzy logic provides a clear direction to align with livestock objectives. The application of fuzzy logic introduces an interactive element to the clustering process. According to Castro et al. [13], animals should ideally display a higher BCS associated with lower EPG and FAMACHA© scores. If partial correlations between these three traits differ, the highest value can serve as a weight in clustering, potentially shifting an animal between groups.

When lacking this correlation insight, multivariate clustering methods might be more prone to not fulfilling livestock interests compared to fuzzy logic. The latter could label an animal as resistant if it is parasitized by non-hematophagous worms, exhibits low anemia (FAMACHA©), and high EPG.

In light of the above, the lower overall accuracy (77.00%) of fuzzy logic in allocating animals into the three groups (resistant, resilient, sensitive) indicates its inadequacy for studying animals' response to parasitism. However, the fuzzy logic approach rectifies the tendency of multivariate methods to overestimate the number of resistant animals, in contrast to literature indicating a higher occurrence of sensitive animals. It is crucial not to confuse the excellence or statistical robustness of these clustering methods with their suitability for livestock applications if used as a selection criterion by producers or in the study of animals’ response to worm infection [2].

Concordance between fuzzy logic results and the described percentage of animals resistant to worm infection [24, 28] suggests that AI-assisted worm infection management benefits livestock practices. Consequently, fuzzy logic constructs a phenotypic profile structure potentially better aligned with livestock interests than multivariate algorithms. Considering that preventing the spread of diseases should be part of good health management practices, a pragmatic measure involves incorporating EPG, BCS, and FAMACHA© information into herd strategies alongside the resources evaluated here. This study underscores that sensitivity to worm infection increases vulnerability, potentially leading to culling due to heightened mortality risk.

4. Conclusion

The utilization of fuzzy logic enabled the creation of response categories to worm infection, aligning with livestock objectives. This underscores its potential as a valuable tool for selecting animals that display greater phenotypic resistance to parasitism.

Conflicts of interest

The authors declare that there are no conflicts of interest.

Author contributions

Conceptualization: W. P. S. Oliveira, N. P. S. Santos and A. M. Araújo. *Data curation*: N. P. S. Santos and M. B. Oliveira. *Investigation*: W. P. S. Oliveira and A. M. Araújo. *Methodology*: N. P. S. Santos, M. B. Oliveira and A. F. Evangelista. *Writing (review and editing)*: W. P. S. Oliveira, N. P. S. Santos, A. F. Evangelista, R. T. Costa Filho and A. M. Araújo.

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