pathogens

MDPI

Article

A Genome-Wide Association Study for Resistance to Tropical Theileriosis in Two Bovine Portuguese Autochthonous Breeds

Diana Valente [1,2,3,*], Octávio Serra [4], Nuno Carolino [1,5,6,7], Jacinto Gomes [6,7,8], Ana Cláudia Coelho [2,3,7], Pedro Espadinha [9], José Pais [10] and Inês Carolino [1,5,11]

1 Centro de Investigação Vasco da Gama, Escola Universitária Vasco da Gama, 3020-210 Coimbra, Portugal; nuno.carolino@iniav.pt (N.C.); ines.carolino@iniav.pt (I.C.)
2 Escola de Ciências Agrárias e Veterinárias, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5000-801 Vila Real, Portugal; accoelho@utad.pt
3 Centro de Ciência Animal e Veterinária, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5000-801 Vila Real, Portugal
4 Instituto Nacional de Investigação Agrária e Veterinária, I.P., Banco Português de Germoplasma Vegetal, Quinta de S. José, S. Pedro de Merelim, 4700-859 Braga, Portugal; octavio.serra@iniav.pt
5 Instituto Nacional de Investigação Agrária e Veterinária, Polo de Inovação da Fonte Boa—Estação Zootécnica Nacional, 2005-424 Santarém, Portugal
6 Centro de Investigação Interdisciplinar em Sanidade Animal, Faculdade de Medicina Veterinária, Universidade de Lisboa, 1300-477 Lisboa, Portugal
7 Laboratório Associado para a Ciência Animal e Veterinária, Faculdade de Medicina Veterinária, Universidade de Lisboa, 1300-477 Lisboa, Portugal
8 Escola Superior Agrária de Elvas, Instituto Politécnico de Portalegre, 7350-092 Elvas, Portugal
9 Associação de Criadores de Bovinos da Raça Alentejana, Monforte Herdade da Coutada Real-Assumar, 7450-051 Assumar, Portugal
10 Associação de Criadores de Bovinos Mertolengos, 7006-806 Évora, Portugal; pais@mertolenga.com
11 Instituto Superior de Agronomia, Universidade de Lisboa, 1349-017 Lisboa, Portugal
* Correspondence: dmsvalente@hotmail.com

Abstract: The control of Tropical Theileriosis, a tick-borne disease with a strong impact on cattle breeding, can be facilitated using marker-assisted selection in breeding programs. Genome-wide association studies (GWAS) using high-density arrays are extremely important for the ongoing process of identifying genomic variants associated with resistance to *Theileria annulata* infection. In this work, single-nucleotide polymorphisms (SNPs) were analyzed in the Portuguese autochthonous cattle breeds Alentejana and Mertolenga. In total, 24 SNPs suggestive of significance ($p \leq 10^{-4}$) were identified for Alentejana cattle and 20 SNPs were identified for Mertolenga cattle. The genomic regions around these SNPs were further investigated for annotated genes and quantitative trait loci (QTLs) previously described by other authors. Regarding the Alentejana breed, the *MAP3K1*, *CMTM7*, *SSFA2*, and *ATG13* genes are located near suggestive SNPs and appear as candidate genes for resistance to Tropical Theileriosis, considering its action in the immune response and resistance to other diseases. On the other hand, in the Mertolenga breed, the *UOX* gene is also a candidate gene due to its apparent link to the pathogenesis of the disease. These results may represent a first step toward the possibility of including genetic markers for resistance to Tropical Theileriosis in current breed selection programs.

Keywords: tick-borne disease; *Theileria annulata*; single-nucleotide polymorphisms (SNPs); marker-assisted selection; Mertolenga breed; Alentejana breed

Citation: Valente, D.; Serra, O.; Carolino, N.; Gomes, J.; Coelho, A.C.; Espadinha, P.; Pais, J.; Carolino, I. A Genome-Wide Association Study for Resistance to Tropical Theileriosis in Two Bovine Portuguese Autochthonous Breeds. *Pathogens* **2024**, *13*, 71. https://doi.org/10.3390/pathogens13010071

Academic Editor: Ana Domingos

Received: 9 December 2023
Revised: 3 January 2024
Accepted: 9 January 2024
Published: 12 January 2024

1. Introduction

Tropical Theileriosis is a tick-borne disease caused by a hemoprotozoan, *Theileria annulata*, which affects cattle production in Europe, Asia, and Africa [1]. This parasite can affect the host's immune system and cause damage to red blood cells, leading to varying degrees of anemia [2]. This will result in production shortfalls and increased mortality and

morbidity rates of parasitized animals. Thus, Tropical Theileriosis causes economic losses associated with reduced production capacity and the need to carry out control for diseases and ticks; for example, through the use of acaricides [3].

Theileriosis control strategies may include curing affected animals and prevention [4]. Curing affected animals can be difficult and involves the administration of substances such as imidocarb, erythromycin, oxytetracycline, quinozoline, and naphthoquinone derivatives (parvaquone and buparvaquone), whose efficacy is questionable [5–7]. In addition, buparvaquone, for example, can leave residues in animal products, such as meat and milk, implying long safety intervals, and its use is, therefore, limited in several countries, including European countries, where its use is not approved by the EMA (European Medicines Agency) [5,8]. In an attempt to control this disease, where it is difficult to achieve a cure, it is possible to resort to culling affected animals, although this results in significant economic losses for the farm [4]. The prevention of Tropical Theileriosis can be based on strategies that include the control of ticks (e.g., use of acaricides), the environment (e.g., biosecurity measures and avoiding movement of animals from non-endemic to endemic areas), and the animal (e.g., selection of resistant animals and use of vaccines) [4,5]. The use of acaricides in the control of ticks and tick-borne diseases is one of the main strategies used, but it is costly [4]. In addition, increasing acaricide resistance is also a concern in the implementation of this control strategy [4,7,9]. Acaricide resistance results from the selection of specific heritable traits in a tick population, resulting from exposure of the population to an acaricide. As a result, there will be an increase in the number of ticks that survive after the administration of the recommended dose of the same acaricide to which resistance already exists [9]. In turn, the use of vaccines, an animal-based control strategy for Tropical Theileriosis, also has some limitations. The only vaccines that appear to be effective are live attenuated vaccines, but more research is needed to fully understand their mechanism of action [5,7]. Subunit vaccines are difficult to obtain, considering the genetic diversity of these parasites [5]. Finally, the use of resistant animals could be another, more sustainable, strategy to minimize the impact of the Tropical Theileriosis [6,8].

The use of animals that are genetically tolerant/resistant to ticks and tick-borne diseases is thus considered the most natural control alternative [10]. Natural disease resistance refers to the inherent ability of an animal to resist diseases when exposed to pathogens without prior exposure or immunization [4]. Several authors have reported that cattle of autochthonous breeds from endemic regions are more resistant than those of exotic breeds [3,11–13]. For example, different responses to *T. annulata* infection have been identified in the Sahiwal breed (*B. indicus*) and the Holstein breed (*B. taurus*) [11,14].

An important prerequisite in breeding strategies for disease tolerance/resistance is the attempt to understand the genetic control mechanisms of diseases. Nowadays, it is known that tick loads in cattle have moderate to high levels of heritability, which can range from 0.40 to 0.54 [15,16]. In addition, some hemoparasitoses, such as those caused by *Anaplasma marginale* and *Ehrlichia ruminantium*, appear to have significant heritabilities, with values of 0.16 and 0.19, respectively [17]. Genome-wide association studies have been conducted for some vector-borne diseases [10]. In addition, single-nucleotide polymorphisms (SNPs) have been tested to identify genetic variants associated with complex traits. SNPs distributed throughout the genome can detect and map mutations underlying variation in target traits by a process called genome-wide association analysis (GWAS) [18]. GWAS allows for the identification of genetic markers, candidate genes, and QTLs for individual traits. The discovery of a quantitative trait locus (QTL) is an important step in identifying and understanding genetic variants associated with economically important phenotypes, and genome-wide association study (GWAS) has become a widely used approach for identifying QTLs and genome regions associated with phenotypes [19]. High-density arrays capable of genotyping thousands of SNPs are already available for cattle, allowing for increased genomic coverage and statistical power [20].

This study aims to identify SNP genetic markers that may be associated with resistance to Tropical Theileriosis in the cattle of the autochthonous Portuguese breeds Alentejana

and Mertolenga and genes or genomic regions that are most likely involved in resistance to this disease. These data will be important information to include in breeding programs for these breeds, which are at risk of extinction and have conservation and improvement programs in place.

2. Materials and Methods

2.1. Sample Characterization

The blood samples used in this study were collected in the Alentejo region of Portugal, the country's leading beef-producing region, with more than 65% of national production. This region is the place of origin of the Portuguese autochthonous breeds under study, namely the Alentejana and the Mertolenga breeds, and is also an endemic region for *T. annulata* [21]. The Alentejana and Mertolenga breeds belong to a group of 15 autochthonous Portuguese cattle breeds and are at risk of extinction [22]. The Alentejana cattle breed has around 22,000 breeding females registered in the herd book, spread over around 174 farms, although only around 8000 are purebred, and the rest are used for crossbreeding with males from exotic international breeds [23]. On the other hand, the Mertolenga cattle breed, which currently has 27,000 breeding females, is the largest of Portugal's 15 autochthonous breeds. Similar to the Alentejana breed, only around 8000 females are purebred, the rest are used to crossbreed with males from exotic international breeds [24].

Initially, 843 blood samples were randomly collected from purebred Alentejana and Mertolenga cattle, which did not show any clinical signs of *T. annulata* infection. The collections were carried out between November 2018 and December 2019 in 420 Alentejana breed animals and 423 Mertolenga breed animals. These animals all belong to farms with extensive or semi-extensive production regimes, so these animals live outdoors and in a pasture.

2.2. Sample Collection

Between 3 and 5 mL of blood were collected from the jugular vein of each animal and stored individually in tubes containing EDTA (ethylenediaminetetraacetic acid). This blood sampling was carried out by the technicians of the cattle associations of the autochthonous breeds under study. The tubes containing the blood sample were frozen at −20 °C before being sent to the laboratory. During transport and storage, the temperature conditions were maintained.

2.3. Sample Processing

Initially, these samples were analyzed at the Molecular Genetics Laboratory of the National Institute for Agricultural and Veterinary Research (INIAV). In the laboratory, 300 µL of each of the 843 blood samples were used to perform DNA extraction using a Cytogene® Blood Kit (Lucknow, India, Cytogene), following the manufacturer's instructions. Thereafter, DNA from each sample was subjected to amplification with the Polymerase Chain Reaction (PCR) of a fragment, with about 319 base pairs (bp), of a *T. annulata* merozoite-piroplasm surface antigen gene, *Tams 1* [25]. In all reactions, a negative sample of *T. annulata* (negative control) was used, without DNA, and a positive sample (positive control), property of the Parasitology Laboratory of the INIAV (Lisbon, Portugal). The amplified samples were analyzed by 1.5% agarose gel electrophoresis, and the gel was visualized with an ultraviolet (UV) transilluminator. Positive and negative PCR controls were introduced in each PCR, and a molecular weight marker (NZYDNA VI) was placed on each gel. Samples were classified as positive (samples infected with *T. annulata*, with the presence of the *Tams 1* gene) and negative (samples not infected with *T. annulata*, without the presence of the *Tams 1* gene). From the 843 blood samples analyzed, 96 samples from animals of the Alentejana breed and 96 samples from animals of the Mertolenga breed were selected. In the case of the animals of the Alentejana breed, all the samples positive for *T. annulata* (30 samples) were used, and the farms to which they belonged were identified. The remaining 66 negative samples were selected from the same farms as the

previous ones. In the case of the Mertolenga breed, we used 48 samples from infected animals and 48 samples from non-infected animals (n = 96), selecting the latter based on the farm to which the infected animals belonged. The presence of the *Tams 1* gene (infected animals) or its absence (non-infected animals) were the phenotypic extremes considered in our study. Thus, infected animals, with the presence of the *Tams 1* gene in the blood sample, were considered susceptible to Tropical Theileriosis, while non-infected animals, without the presence of the *Tams 1* gene in the blood sample, were considered resistant to Tropical Theileriosis.

2.4. SNP Genotyping and GWAS Analysis

All 192 samples were genotyped in two plates of 96 samples in the Axiom™ Bovine Genotyping 100K Array, 1 plate for each breed, in a laboratory providing animal health and food safety services (Segalab, Portugal), following the best practices workflow from the manufacturer. The "BestandRecommended" SNPs were selected for the analysis of both breeds. PLINK v1.9 was used for quality control [26]. SNPs were filtered out whenever the minor allele frequency (--maf) was below 5% and missing data (--geno) was higher than 10%. Similarly, samples were filtered out when there was 10% or more missing data (--mind). To account for population structure, samples were filtered based on cryptic relatedness (--min 0.2), and their distribution was inferred by means of a principal component analysis (--pca var-wts). Whenever a principal component was responsible for a significative separation of samples into groups, which was not expected from sample records, it was used as a covariate for the association analysis. Genome-wide association analysis was performed in PLINK under the logistic model for disease traits (--logistic). Case/control phenotypes for *T. annulata* were included in the phenotype files (--pheno). The origin of each sample, namely its breeder or the district of provenance, was used as a covariate (--covar). The association was evaluated using quantile–quantile plots. The p-values for all SNPs were adjusted for the false discovery rate (FDR). Also, the threshold of significance was calculated following the Bonferroni correction.

2.5. Data Analysis

Data analysis was supported by querying the Bovine Mine and National Center for Biotechnology Information databases [27,28]. When analyzing the data using these databases, the aim was to identify the overlap of suggestive SNPs with possible genes and QTLs or to identify genes in their vicinity.

3. Results

3.1. Descriptive Statistics

In the sample initially used (n = 843), it was possible to find positivity to *T. annulata* of 7.10% (30/420) in Alentejana animals and 14.4% (61/423) in Mertolenga animals [21]. As mentioned above, we selected 96 Alentejana animals and 96 Mertolenga animals, whose characteristics are described in the table below (Table 1).

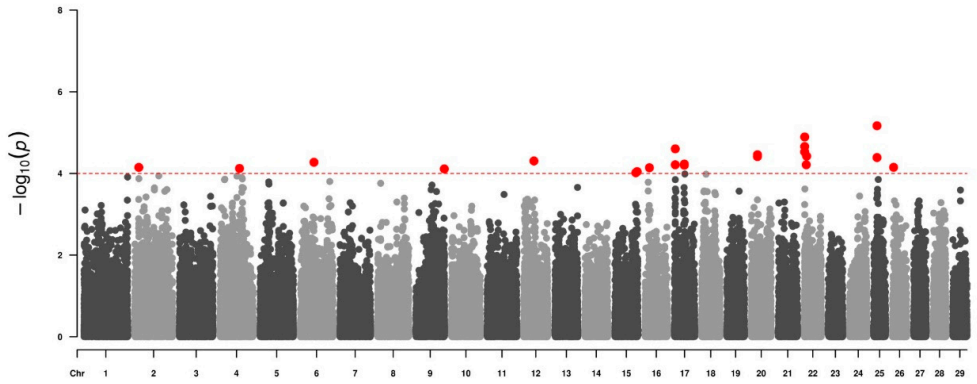
Table 1. Characteristics of the Alentejana and Mertolenga animals under study.

Parameter		Alentejana	Mertolenga
***T. annulata* Infection**	**Positive**	30 (31.25%)	48 (50.00%)
	Negative	66 (68.75%)	48 (50.00%)
Age	**Youngest animal**	8 months	1 month
	Oldest animal	14 years and 2 months	8 years and 5 months
Sex	**Male**	5 (5.20%)	3 (3.10%)
	Female	91 (94.8%)	93 (96.90%)
Number of farms		14	13

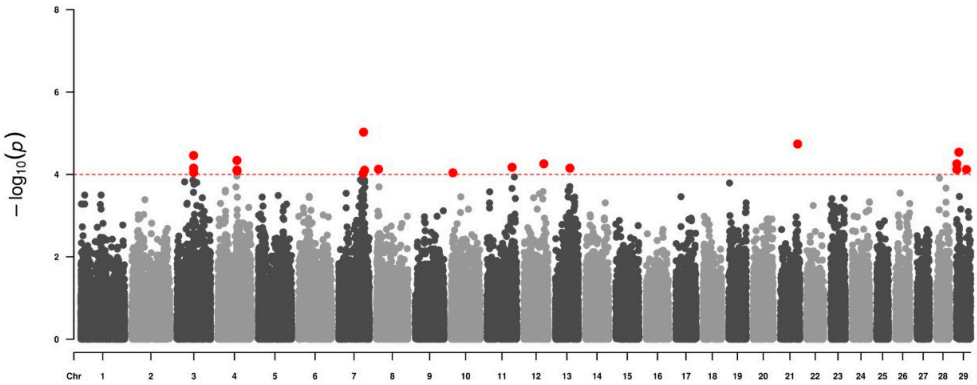
3.2. Genome-Wide Associations

To identify SNP genetic markers and QTLs for resistance to Tropical Theileriosis, we performed a GWAS using a genotyping approach. After implementing data quality control measures, out of the 100,000 SNPs on the array, 75,126 SNPs were used in the association test for the Alentejana breed and 81,357 SNPs were used for the Mertolenga breed, and the analysis was performed for each breed separately.

Considering an initial p-value ≤ 0.05, it was possible to find 7833 significant SNPs in the Alentejana breed and 7157 significant SNPs in the Mertolenga breed. All SNPs were classified as non-significant based on the adjusted p-values after the FDR. Furthermore, the Bonferroni correction also established a threshold of significance lower than the lowest p-value found. Despite this, based on other GWAS works available in the literature, it was decided that the suggestive value of significance to be used in this work would be p-value $\leq 10^{-4}$ (Figure 1) [29–31]. Thus, it was possible to find 24 significant SNPs for Alentejana cattle and 20 significant SNPs for Mertolenga cattle (Table 2). In this table, we can see that for both breeds, the protective allele of the identified SNPs appears in a higher percentage in the animals under study. Thus, we found that the protective allele appears more frequently in 75% of the SNPs studied in the Alentejana breed and 80% of the SNPs studied in the Mertolenga breed.



(**a**)



(**b**)

Figure 1. Manhattan plot of the association study for resistance to tropical theileriosis in two Portuguese autochthonous bovine breeds. The genome-wide significance threshold is indicated by the dashed line ($p < 10^{-4}$). The red dots above the threshold line represent the SNPs considered as significant in this work. The position of the bovine chromosome is shown on the x-axis. The strength of association for a GWAS single-locus mixed model is shown on the y-axis. (**a**) Data from Alentejana breed animals. (**b**) Data from Mertolenga breed animals.

Table 2. SNPs suggestive of genome-wide significance, with *p*-values and the allele associated with resistance to Tropical Theileriosis (Chr—chromosome; A1—minor allele; BETA—regression coefficient).

Alentejana Breed							
Marker	**Chr**	**Position/ Variant**	***p*-Value**	**A1**	**BETA**	**Protective Allele**	**Reference Allele/Alternative Allele**
rs29016369	25	11866965 Intergenic	6.80×10^{-6}	T	2.045	C	C/T
rs382748014	22	1—175689 Intergenic	1.28×10^{-5}	A	2.190	G	A/G
rs136686350	22	1079338 Intron	2.19×10^{-5}	T	2.162	C	C/T
rs42824138	17	3176994 Intron	2.50×10^{-5}	A	1.767	G	A/G
rs42349624	22	1012010 Intron	2.97×10^{-5}	C	2.017	T	T/C
rs110733319	22	1130073 Intergenic	2.97×10^{-5}	T	2.017	G	G/T
rs41580257	20	22411430 Intron	3.48×10^{-5}	A	2.100	G	G/A
rs109220983	22	8175191 Intergenic	3.77×10^{-5}	C	2.152	T	T/C
rs110456301	20	22270511 Intergenic	3.85×10^{-5}	T	1.842	G	T/G
rs136677596	20	22278044 Upstream gene variant	3.85×10^{-5}	T	1.842	C	T/C
rs134209239	25	11945164 Intergenic	4.08×10^{-5}	C	1.751	T	C/T
rs110136753	12	36966751 Intergenic	4.94×10^{-5}	T	1.621	C	T/C
rs137404731	6	49298093 Intergenic	5.33×10^{-5}	A	−2.453	A	G/A
rs135649048	17	35855903 Intergenic	5.89×10^{-5}	T	1.481	C	C/T
rs110248505	17	3089327 Intron	6.12×10^{-5}	A	1.688	G	A/G
rs378877063	22	6853730 Intron	6.12×10^{-5}	T	1.937	C	C/T
rs133854848	17	35658672 Intergenic	6.29×10^{-5}	A	1.615	G	G/A
rs42082138	26	4547983 Intergenic	7.09×10^{-5}	A	−1.996	A	G/A
rs42238085	2	14716248 Intron	7.11×10^{-5}	A	−1.701	A	G/A
rs134193812	16	15787680 Intergenic	7.24×10^{-5}	C	−1.530	C	C/T
rs137244944	4	70697022 Upstream gene variant	7.53×10^{-5}	G	−1.827	G	G/A

Table 2. *Cont.*

Marker	Chr	Position/ Variant	*p*-Value	A1	BETA	Protective Allele	Reference Allele/Alternative Allele
Alentejana Breed							
rs41657708	9	103006480 Intergenic	7.74×10^{-5}	T	−1.743	T	C/T
rs136575474	15	81387903 Intron	8.99×10^{-5}	G	1.340	T	G/T
rs41782203	15	76586569 Intron	9.60×10^{-5}	A	1.656	G	G/A
Mertolenga Breed							
rs41625107	7	89404622 Intergenic	9.40×10^{-6}	G	1.584	A	A/G
rs385061716	21	62178639 Intergenic	1.82×10^{-5}	T	1.776	C	C/T
rs137077511	29	9372082 Intergenic	2.88×10^{-5}	T	1.638	G	T/G
rs210844007	3	59423141 Intron	3.46×10^{-5}	G	1.580	A	A/G
rs136003479	4	68835630 Downstream gene variant	4.55×10^{-5}	A	1.330	G	G/A
rs42966583	12	71327190 Intron	5.51×10^{-5}	A	−1.378	A	A/C
rs109210201	29	1806321 Intergenic	5.53×10^{-5}	C	1.784	A	C/A
rs110183014	11	89708117 Intergenic	6.69×10^{-5}	A	−1.494	A	G/A
rs43338206	3	59696522 Intron	7.01×10^{-5}	T	1.532	C	T/C
rs110582951	13	52653719 Intergenic	7.05×10^{-5}	G	1.397	A	G/A
rs41588323	8	7368884 Intergenic	7.46×10^{-5}	C	2.140	T	T/C
rs42492357	29	1982095 Intergenic	7.59×10^{-5}	G	1.490	A	A/G
rs41651830	29	36432759 Upstream gene variant	7.59×10^{-5}	C	1.490	T	T/C
rs109072096	4	68841016 Upstream and Downstream gene variant	7.84×10^{-5}	A	1.246	G	G/A
rs109619291	7	92837313 Intergenic	7.91×10^{-5}	T	1.301	C	C/T
AX-212327028 *	4	69412929 *	8.15×10^{-5}	C	2.039	A	A/C
rs43338222	3	59690463 Missense variant and intron	9.01×10^{-5}	T	1.508	C	C/T

Table 2. *Cont.*

Alentejana Breed							
Marker	**Chr**	**Position/ Variant**	***p*-Value**	**A1**	**BETA**	**Protective Allele**	**Reference Allele/Alternative Allele**
rs110062605	10	6197570 Intergenic	9.14×10^{-5}	A	1.340	C	C/A
rs133541497	7	88255064 Intron	9.41×10^{-5}	A	−1.278	A	C/A
rs137232658	7	88256048 Intron	9.41×10^{-5}	G	−1.278	G	A/G

* No rsID SNP or variant could be found; thus, the Affymetrix Axiom Bovine ID was presented.

For the Alentejana breed, considering the 24 SNPs suggestive of genomic significance for resistance to Tropical Theileriosis, it was not possible to find any overlapping QTLs. On the other hand, in the case of the Mertolenga breed, considering the twenty SNPs suggestive of genomic significance, seven QTLs were found in the vicinity of the suggestive SNPs, distributed over four chromosomes (chromosomes 3, 7, 8, and 29) (Table 3).

Table 3. Quantitative trait loci already described that were found based on the SNPs with genomic significance considered for the Mertolenga breed (Chr—chromosome).

Marker	Chr	QTL ID	QTL Trait	References
rs43338206	3	22779	Average daily gain *B. taurus*	[32]
rs41625107	7	151659	Muscle carnosine content	[33]
rs41625107	7	151673	Muscle creatine content	[33]
rs41625107	7	164401	Body weight (birth)	[34]
rs41625107	7	164580	Longissimus muscle area	[34]
rs41588323	8	151760	Muscle creatinine content	[33]
rs137077511	29	116645	Milk glycosylated kappa-casein percentage	[35]

In addition to the identification of QTLs based on SNPs suggestive of genomic significance, the genes where these SNPs overlapped with or the genes upstream and downstream of them, in the case of intergenic variants, were also considered. Thus, it was possible to identify different genes on chromosomes 2, 4, 6, 9, 12, 15, 16, 17, 20, 22, 25, and 26 for the Alentejana breed (Table 4) and on chromosomes 3, 4, 7, 8, 10, 11, 12, 13, 21, and 29 for the Mertolenga breed (Table 5).

Table 4. Identification of genes using SNPs with significance for the Alentejana breed (*Bos taurus*) (Chr—chromosome).

Marker	*p*-Value	Chr	Position	Gene	Gene Location (bp) (Start-End)
rs29016369	6.80×10^{-6}	25	11866965	*SHISA9—shisa family member 9*	11633241-11647753
					11633245-12158399
rs382748014	1.28×10^{-5}	22	1175689	*EGFR—epidermal growth factor receptor*	905960-1121554
				RF00003	1258027-1258168
rs136686350	2.19×10^{-5}	22	1079338	*EGFR—epidermal growth factor receptor*	905960-1121554

Table 4. *Cont.*

Marker	*p*-Value	Chr	Position	Gene	Gene Location (bp) (Start-End)
rs42824138	2.50×10^{-5}	17	3176994	*ENSBTAG00000024545*	3009649-3332773
				DCHS2—dachsous cadherin-related 2	3137604-3333575
rs42349624	2.97×10^{-5}	22	1012010	*EGFR—epidermal growth factor receptor*	899974-1121540
					905960-1121554
rs110733319	2.97×10^{-5}	22	1130073	*EGFR—epidermal growth factor receptor*	899974-1121540
					905960-1121554
				RF00003	1258027-1258168
rs41580257	3.48×10^{-5}	20	22411430	*MAP3K1—mitogen-activated protein kinase kinase kinase 1*	22340163-22417428
rs109220983	3.77×10^{-5}	22	8175191	*ENSBTAG00000051119*	8163685-8167126
				RF00026	8222734-8222838
rs110456301	3.85×10^{-5}	20	22270511	*LOC112443032—uncharacterized*	22159612-22183599
				MIER3—MIER family member 3	22279228-22305654
rs136677596	3.85×10^{-5}	20	22278044	*LOC112443032—uncharacterized*	22159612-22183599
				MIER3—MIER family member 3	22279228-22305654
rs134209239	4.08×10^{-5}	25	11945164	*SHISA9—shisa family member 9*	11633245-12158399
rs110136753	4.94×10^{-5}	12	36966751	*ATP12A—ATPase H/K transporting non-gastric alpha2 subunit*	36642635-36664187
				ENSBTAG00000049928	37397698-37398144
rs137404731	5.33×10^{-5}	6	49298093	*RF00156*	49020641-49020774
				RF00019	49412387-49412498
rs135649048	5.89×10^{-5}	17	35855903	*TRPC3—transient receptor potential cation channel subfamily C member 3*	35728366-35800211
				FSTL5—follistatin-like 5	36260758-37189201
rs110248505	6.12×10^{-5}	17	3089327	*LOC107133268—protocadherin-16-like*	3009266-3011829
				ENSBTAG00000024545	3009649-3332773
rs378877063	6.12×10^{-5}	22	6853730	*CMTM7—Bos taurus CKLF-like MARVEL transmembrane domain-containing 7*	6821672-6869727
					6821790-6869725
rs133854848	6.29×10^{-5}	17	35658672	*LOC782754—mpv17-like protein 2*	35638835-35639137
				TRPC3—transient receptor potential cation channel subfamily C member 3	35728366-35800211
rs42082138	7.09×10^{-5}	26	4547983	*PCDH15—protocadherin-related 15*	4509270-5569299
rs42238085	7.11×10^{-5}	2	14716248	*SSFA2—sperm-specific antigen 2*	14654230-14750696
				ITPRID2—Bos taurus ITPR interacting domain-containing 2	14654230-14751034
rs134193812	7.24×10^{-5}	16	15787680	*BRINP3—BMP/retinoic acid inducible neural specific 3*	15141936-15631140
				RF00001	16102665-16102785
rs137244944	7.53×10^{-5}	4	70697022	*C4H7orf31—chromosome 4 C7orf31 homolog*	70687353-70727845
rs41657708	7.74×10^{-5}	9	103006480	*LOC101907681—uncharacterized*	102848965-102870347
				LOC112448098—uncharacterized	103129637-103132019

Table 4. *Cont.*

Marker	*p*-Value	Chr	Position	Gene	Gene Location (bp) (Start-End)
rs136575474	8.99×10^{-5}	15	81387903	*LOC107133203—olfactory receptor 1S1-like*	81383730-81385093
				LOC104974344—olfactory receptor 10Q1	81397109-81421347
rs41782203	9.60×10^{-5}	15	76586569	*ATG13—Bos taurus autophagy-related 13*	76578054-76620037
					76578279-76620035

Table 5. Identification of genes using SNPs with significance for the Mertolenga breed (*Bos taurus*) (Chr—chromosome).

Marker	*p*-Value	Chr	Position	Gene	Gene Location (bp) (Start-End)
rs41625107	9.40×10^{-6}	7	89404622	*MIR3660—microRNA 3660*	89558103-89558182
				ENSBTAG00000048981	88840369-88848347
rs385061716	1.82×10^{-5}	21	62178639	*RF00003—RNA, U1 small nuclear 85, pseudogene*	62091713-62091865
				LOC112443166—uncharacterized	62865898-62974123
rs137077511	2.88×10^{-5}	29	9372082	*EED—embryonic ectoderm development*	9265439-9296624
				LOC112444890—uncharacterized	9426391-9430563
rs210844007	3.46×10^{-5}	3	59423141	*SSX2IP—Bos taurus SSX family member 2 interacting protein*	59398296-59456577
rs136003479	4.55×10^{-5}	4	68835630	*RF02043*	68836226-68836391
rs42966583	5.51×10^{-5}	12	71327190	*ENSBTAG00000026070*	71263913-71411435
				LOC107131273—multidrug resistance-associated protein 4-like	71265415-71400436
rs109210201	5.53×10^{-5}	29	1806321	*SLC36A4—solute carrier family 36 member 4*	1701573-1743386
				MTNR1B—melatonin receptor 1B	1901714-1916511
rs110183014	6.69×10^{-5}	11	89708117	*RF00017—RNA, 7SL, cytoplasmic 825, pseudogene*	89685923-89686207
				ENSBTAG00000052434	89823864-89861691
rs43338206	7.01×10^{-5}	3	59696522	*UOX—Bos taurus urate oxidase*	59636716-59736408
				DNASE2B—deoxyribonuclease 2 beta	59681735-59700078
				RPF1—ribosome production factor 1 homolog	59600697-59617167
rs110582951	7.05×10^{-5}	13	52653719	*TMC2—transmembrane channel-like 2*	52539174-52640959
				SNRPB—small nuclear ribonucleoprotein polypeptides B and B1	52666459-52675562
rs41588323	7.46×10^{-5}	8	7368884	*ENSBTAG00000039873*	7325501-7331864
				TRNAC-GCA—tRNA-Cys	7430900-7430971
rs42492357	7.59×10^{-5}	29	1982095	*MTNR1B—melatonin receptor 1B*	1901714-1916511
				FAT3—FAT atypical cadherin 3	1991657-2638923
rs41651830	7.59×10^{-5}	29	36432759	*ZBTB44—zinc finger and BTB domain-containing 44*	36401292-36460165
					36408247-36429241

Table 5. *Cont.*

Marker	*p*-Value	Chr	Position	Gene	Gene Location (bp) (Start-End)
rs109072096	7.84×10^{-5}	4	68841016	*RF02041*	68840319-68840692
				RF02040	68842022-68842077
rs109619291	7.91×10^{-5}	7	92837313	*ENSBTAG00000054282*	92782983-92822683
				LOC100848699—uncharacterized	92887690-92904398
AX-212327028 *	8.15×10^{-5}	4	69412929	*RF00100*	69383582-69383863
				LOC112446335—uncharacterized	69487699-69491861
rs43338222	9.01×10^{-5}	3	59690463	*DNASE2B—deoxyribonuclease 2 beta*	59681735-59700078
					59681727-59699694
rs110062605	9.14×10^{-5}	10	6197570	*DRD1—Bos taurus dopamine receptor D1*	5715882-5718113
				LOC112448549—uncharacterized	6357822-6363522
rs133541497	9.41×10^{-5}	7	88255064	*MEF2C—myocyte enhancer factor 2C*	88250023-88407702
rs137232658	9.41×10^{-5}	7	88256048	*MEF2C—myocyte enhancer factor 2C*	88250023-88407702

* No rsID SNP could be found; thus, the Affymetrix Axiom Bovine ID was presented.

4. Discussion

In this work, GWAS was performed using a high-density bovine SNP array that allowed the identification of 24 significant SNPs for Alentejana breed cattle and 20 significant SNPs for Mertolenga breed cattle ($p \leq 10^{-4}$). For these SNPs, in both breeds, we found that the protective allele is the most prevalent. In addition, only in the case of the Mertolenga breed was it possible to identify seven QTLs already described, associated with SNPs suggestive of resistance/susceptibility to Theileriosis. These QTLs are associated with traits such as average daily gain, muscle carnosine, creatine and creatinine content, body weight at birth, larger muscle area, and percentage of glycated kappa-casein in milk. These data are extremely important because the genetic selection of animals may be considered important health traits but cannot neglect the productive traits of these animals. Thus, the use of QTLs in genomic selection studies and breeding programs makes it possible to maximize genetic and economic gains [36]. Thus, these programs may allow the selection of animals with higher combined economic value for the next generation by combining productive and non-productive traits, such as resistance to Theileriosis [37]. In the case of the breeds under study, we think these data are even more valuable, as these are two autochthonous Portuguese breeds at risk of extinction. Thus, the selection of productive and healthy characteristics increases the interest of livestock producers in breeding these animals, which could contribute to an increase in the number of animals. On the other hand, selection for resistance to this disease contributes to animal health and welfare and to reducing the use of chemical substances as an approach to treating and controlling Tropical Theileriosis.

It was also possible to identify several annotated genes that overlap with the suggestive SNPs from GWAS, or in their vicinity. For the Alentejana breed, it was possible to find genes associated with the regulation of cell proliferation, differentiation, and survival, such as *EGFR* (*epidermal growth factor receptor*), cell growth, such as *DCHS2* (*dachsous cadherin-related 2*), and the formation of plasma cation channels, such as *TRPC3* (*transient receptor potential cation channel subfamily C member 3*) [38–40]. In addition to these functions at the cellular level, of the genes described, the *MAP3K1* (*mitogen-activated protein kinase kinase 1*) gene was identified, which acts in the MAPK pathway, a signal transduction pathway that modulates physiological and pathophysiological cellular responses. In this pathway, mitogen-activated protein kinases regulate important cellular processes such as proliferation, stress response, apoptosis, and immune defense, regulating the production

of T helper 1 (Th1) and T helper 2 (Th2) lymphocyte responses. Currently, the ability of protozoan parasites such as *Trypanosoma cruzi*, *Trypanosoma congolense*, and *Leishmania* spp. to modulate the host immune response by intervening in the MAPK pathway to favor their replication and survival has been described [41,42]. Another gene recognized was *CMTM7* (*KLF-like MARVEL transmembrane domain-containing 7*), which belongs to the superfamily encoding chemokine-like factors. A lack of *CMTM7* has already been shown to cause a reduction in the innate B-cell population and lead to natural IgM and IL-10 deficiency [43]. IL 10 is one of the interleukins present in the highest concentration when cattle are infected with *T. annulata* and is essential in the development of the immune response against this agent [44]. In turn, the *SSFA2* (*sperm-specific antigen 2*) gene was identified, whose presence has already been reported to be associated with greater resistance to the development of clinical mastitis in cattle [45]. In addition to all these, the *ATG13* (*autophagy-related 13*) gene was also identified as being responsible for cellular autophagy, i.e., programmed cell death when cells are aged, degenerated, or non-functional. The action of this gene in the autophagy process in cells infected with the Bovine Viral Diarrhea Virus (BVDv) has already been described [46]. The BVDv is an intracellular pathogen at a certain stage of its cycle, like *T. annulata* [47].

Interestingly, two genes were identified in the group of Alentejana animals that seem to be associated with neurotransmitter concentration. It is known that the abnormal concentration of neurotransmitters is one of the factors that affect the health status, temperament, and welfare of animals, but the genetic basis of this abnormality is still unknown [48]. Despite this, there are already references that the *PCDH15* gene (*protocadherin-related 15*), which was identified in this work, may be associated with the regulation of this concentration. On the other hand, it was also possible to identify the *LOC107133268* gene (*protocadherin-16-like*), whose functions are not yet fully described in cattle, but the homolog, in humans, seems to be involved in the modulation of synaptic transmission and the generation of specific synaptic connections [49]. In addition, the genes *LOC107133203* (*olfactory receptor 1S1-like*) and *LOC104974344* (*olfactory receptor 10Q1*), which encode olfactory receptor proteins responsible for the recognition and transduction of olfactory signals, have also been identified and can trigger a neuronal response that triggers the perception of an odor [50].

In addition, we identified genes potentially associated with resistance to Theileriosis in Alentejana breed animals that appear to have significant productive importance, such as the *ATP12A* (*ATPase H/K transporting non-gastric alpha2 subunit*), *SHISA9* (*shisa family member 9*), and *FSTL5* (*follistatin-like 5*) genes. The *ATP12A* gene encodes the H+/K+ ATPase type 2 protein, a membrane protein involved in transmembrane cation transport, which is present in sperm and acts in the acrosome reaction at fertilization [51]. On the other hand, the *SHISA9* gene is associated with pre-weaning growth, while the *FSTL5* gene appears to be associated with muscle hypertrophy in cattle, inducing follistatin to increase insulin action at the skeletal muscle level [52–55]. Finally, the *BRINP3* (*BMP/retinoic acid inducible neural-specific 3*) gene was also identified, for which its association with meat quality and fertility in heifers is reported [56,57].

Regarding the genes identified, there is an overlap of two SNPs with the *SHISA9* and *EGFR* genes, which affect the animals' productive capacity and cell regulation, respectively. In addition, one SNP overlaps with the *DCHS2*, *MAP3K1*, *CMTM7*, *PCDH15*, *SSFA2*, and *ATG13* genes, most of which act in cell regulation and protective cell response. All other genes described are near the SNPs identified.

In the case of the Mertolenga breed, it was also possible to identify genes with different functions. Thus, the UOX (Bos taurus urate oxidase) gene was identified, which encodes the urate oxidase enzyme and has the function of degrading uric acid, a hematological parameter that is increased in animals infected with *T. annulata* [58,59]. In addition, the *TMC2* (*transmembrane channel-like 2*) gene, which encodes proteins responsible for the formation of mechanosensitive ion channels at the tips of sensory cells in the inner ear, has been identified in mammals [60]. In humans, it is reported to be associated with hearing loss and epidermodysplasia verruciformis [61,62]. Cumulatively, the *ZBTB44* (*zinc finger and*

BTB domain-containing 44) gene has been identified and appears to be associated with the macrophage-dependent immune response in *Mycobacterium avium* subsp. paratuberculosis infection in cattle [63].

Regarding genes associated with production, it was possible to identify the *EED* (*embryonic ectoderm development*) gene, whose association with the milk production capacity of cattle has already been reported [64]. In addition, the *LOC107131273* gene (*multidrug resistance-associated protein 4-like*) was identified, for which there is an indication of differential expression in cows pregnant with large fetuses, which leads to the development of dystocia, with significant impacts on production [65]. Furthermore, the *MTNR1B* (*melatonin receptor 1B*) gene has been identified, which is expressed in mammalian oocytes, and the *TRNAC-GCA* (*tRNA-Cys*) gene appears to be associated with sperm quality [66]. In addition to these, the *DRD1* (*dopamine receptor D1*) gene, which encodes the dopamine D1 receptor protein, has been identified. These receptors are prime candidates in the regulation of energy for the maintenance of homeostasis and are implicated in the regulation of feeding behavior in cattle [67]. Finally, the *MEF2C* (*myocyte enhancer factor 2C*) gene encoding a myocyte enhancer protein was identified and is important for skeletal, cardiac, and smooth muscle development [68,69].

For the Mertolenga breed, two SNPs were found to overlap with the *MEF2C* gene and one SNP with the *LOC170131273*, *UOX*, and *ZBTB44* genes. In addition, the *UOX* gene is also found to overlap with a QTL (associated with average daily gain). This gene is a strong candidate for resistance to Tropical Theileriosis due to the apparent link with the pathogenesis of the disease, warranting further investigation. In addition, the fact that it is related to a QTL associated with average daily gain could also be a good indicator, since one of the losses associated with infection by *T. annulata* is reduced productivity [1]. All other genes recorded are near the significant SNPs identified.

In beef cattle, it is known that it is of utmost importance to increase the ability to resist diseases, which is strongly associated with their immune performance. However, the productive traits of these animals cannot be disregarded, meaning that genes associated with the production of more muscle, better quality meat, or even milk in the case of suckler females are of utmost importance.

To the best of the authors' knowledge, there has been no other published work analyzing GWAS data from the autochthonous Portuguese Alentejana and Mertolenga breeds. As such, this is a study that contributes to deepening genomic knowledge of Portuguese genetic resources. On the other hand, the authors are also unaware of any similar work aimed at associating resistance/tolerance to Tropical Theileriosis using GWAS. Despite this, it was found that some functions of genes associated with resistance to other parasitic diseases, such as Amoebiasis, Trypanosomosis, Toxoplasmosis, and Leishmaniasis, are also common to candidate genes for resistance to Theileriosis and were identified in this study. Thus, we highlighted the action on the cell membrane (*CMTM7*, *TMC2*, and *ATP12A* genes), ATP binding (*ATP12A* gene), and immune response (*MAP3K1*, *CMTM7*, *SSFA2*, *ATG13*, and *ZBTB44* genes) [70]. This work then made it possible to identify some SNPs suggestive of an association with resistance/tolerance to Tropical Theileriosis and the genes and QTLs that overlap or are in the vicinity. In the future, it is important to replicate the results presented here in another sample of animals to confirm the biological and/or metabolic action of the SNPs and QTLs indicated in beef cattle, and, in particular, in the autochthonous Portuguese breeds Alentejana and Mertolenga, as many of them have not yet been characterized, or the existing information is only described in other species. Furthermore, considering that resistance to Tropical Theileriosis is a polygenic trait, it would be interesting to develop a genomic selection study capable of providing information on the evolution of the genomic sites that control this trait and that could provide us with targets for the genetic selection of the most resistant animals [36].

5. Conclusions

In this work, 24 candidate SNPs for resistance to *T. annulata* infection were identified in the Portuguese Alentejana autochthonous breed and 20 candidate SNPs were identified in the Portuguese Mertolenga autochthonous breed. For both breeds, the protective allele of the identified SNPs appears at a higher percentage in the animals under study. Also, seven QTLs were found in the Mertolenga breed, of which one overlaps with the candidate gene *UOX*. This gene appears to be associated with the pathogenesis of Tropical Theileriosis. In the case of the Alentejana breed, the *MAP3K1*, *CMTM7*, *SSFA2*, and *ATG13* genes will be good candidate genes for resistance to Tropical Theileriosis due to their importance in regulating the immune response or their already described impact on resistance to other diseases. Thus, due to the importance that these genes seem to have in Tropical Theileriosis, further studies will be required, focusing on the SNPs identified in this work. In this way, this study is the first step in identifying markers that could be applied in breeding programs for both breeds under study.

Author Contributions: Conceptualization, D.V., I.C. and J.G.; methodology, I.C., D.V. and O.S.; software, O.S., I.C. and D.V.; validation, O.S., I.C., D.V., J.G. and N.C.; formal analysis, O.S., I.C. and D.V.; investigation, D.V. and I.C.; resources, J.P. and P.E.; data curation, O.S., I.C., D.V., J.G. and N.C.; writing—original draft preparation, D.V.; writing—review and editing, I.C., O.S., A.C.C., J.G., D.V., N.C., J.P. and P.E.; supervision, I.C.; project administration, J.G. and I.C.; funding acquisition, J.G. and I.C. All authors have read and agreed to the published version of the manuscript.

Funding: The study was funded by LEAP-Agri (A Long-term EU-Africa Research and Innovation Partnership on Food and Innovation on Food and Nutrition Security and Sustainable Agriculture), project No. 220-MeTVAC (Ecosmart Alternative Control Strategies against *Theileria annulata* and its Tick Vectors), and Fundação para a Ciência e a Tecnologia, Portugal, with the reference LEAPA-gri/0005/2017.

Institutional Review Board Statement: The animal study protocol was approved by the Ethics Committee of the University of Trás-os-Montes e Alto Douro (Doc8-CE-UTAD-2023 of 17 February 2023).

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets presented in this article are not readily available because the data are part of an ongoing study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Gharbi, M.; Darghouth, M.A.; Elati, K.; Al-Hosary, A.A.T.; Ayadi, O.; Salih, D.A.; El Hussein, A.M.; Mhadhbi, M.; Khbou, M.K.; Hassan, S.M.; et al. Current status of tropical theileriosis in Northern Africa: A review of recent epidemiological investigations and implications for control. *Transbound. Emerg. Dis.* **2020**, *67*, 8–25. [CrossRef] [PubMed]
2. Pandey, V.; Nigam, R.; Bachan, R.; Sudan, V.; Jaiswal, A.K.; Shankar, D.; Kumar, R.; Mandil, R.; Yadav, B. Oxidative and haemato-biochemical alterations in theileriosis affected cattle from semi-arid endemic areas of India. *Indian J. Anim. Sci.* **2017**, *87*, 846–850. [CrossRef]
3. Rashid, M.; Akbar, H.; Rashid, I.; Saeed, K.; Ahmad, L.; Ahmad, A.S.; Shehzad, W.; Islam, S.; Farooqi, S. Economic Significance of Tropical Theileriosis on a Holstein Friesian Dairy Farm in Pakistan. *J. Parasitol.* **2018**, *104*, 310–312. [CrossRef] [PubMed]
4. Shyma, K.P.; Gupta, J.P.; Singh, V. Breeding strategies for tick resistance in tropical cattle: A sustainable approach for tick control. *J. Parasit. Dis.* **2015**, *39*, 1–6. [CrossRef] [PubMed]
5. Jenkins, C. Bovine theileriosis in Australia: A decade of disease. *Microbiol. Aust.* **2017**, *2002*, 15–19. [CrossRef]
6. Kasaija, P.D.; Estrada-Peña, A.; Contreras, M.; Kirunda, H.; de la Fuente, J. Ticks and Tick-borne Diseases Cattle ticks and tick-borne diseases: A review of Uganda's situation. *Ticks Tick Borne Dis.* **2021**, *12*, 101756. [CrossRef] [PubMed]
7. Morrison, W.I. The aetiology, pathogenesis and control of theileriosis in domestic animals Diseases caused by *Theileria* species. *Rev. Sci. Tech.* **2015**, *34*, 599–611. [CrossRef]
8. Valente, D.; Gomes, J.; Coelho, A.C.; Carolino, I. Genetic Resistance of Bovines to Theileriosis. *Animals* **2022**, *12*, 2903. [CrossRef] [PubMed]
9. Dzemo, W.D.; Thekisoe, O.; Vudriko, P. Development of acaricide resistance in tick populations of cattle: A systematic review and meta-analysis. *Heliyon* **2022**, *8*, e08718. [CrossRef] [PubMed]
10. Bahbahani, H.; Hanotte, O. Genetic resistance: Tolerance to vector-borne diseases and the prospects and challenges of genomics. *Rev. Sci. Tech.* **2015**, *34*, 185–197. [CrossRef]

11. Glass, E.J.; Jensen, K. Resistance and susceptibility to a protozoan parasite of cattle—Gene expression differences in macrophages from different breeds of cattle. *Vet. Immunol. Immunopathol.* **2007**, *120*, 20–30. [CrossRef] [PubMed]
12. Kumar, A.; Gaur, G.K.; Gandham, R.K.; Panigrahi, M.; Ghosh, S.; Saravanan, B.C.; Bhushan, B.; Tiwari, A.K.; Sulabh, S.; Priya, B.; et al. Global gene expression profile of peripheral blood mononuclear cells challenged with *Theileria annulata* in crossbred and indigenous cattle. *Infect. Genet. Evol.* **2016**, *47*, 9–18. [CrossRef]
13. Nazifi, S.; Razavi, S.M.; Reiszadeh, M.; Esmailnezhad, Z.; Ansari-Lari, M.; Hasanshahi, F. Evaluation of the resistance of indigenous Iranian cattle to *Theileria annulata* compared with Holstein cattle by measurement of acute phase proteins. *Comp. Clin. Path.* **2010**, *19*, 155–161. [CrossRef]
14. Glass, E.J.; Preston, P.M.; Springbett, A.; Craigmile, S.; Kirvar, E.; Wilkie, G.; Brown, C.D. *Bos taurus* and *Bos indicus* (Sahiwal) calves respond differently to infection with *Theileria annulata* and produce markedly different levels of acute phase proteins. *Int. J. Parasitol.* **2005**, *35*, 337–347. [CrossRef]
15. Tabor, A.E.; Santos, I.K.F.D.M.; Boulanger, N. Editorial: Ticks and Host Immunity—New Strategies for Controlling Ticks and Tick-Borne Pathogens. *Front. Immunol.* **2021**, *12*, 10–12. [CrossRef] [PubMed]
16. Otto, P.I.; Guimarães, S.E.F.; Verardo, L.L.; Azevedo, A.L.S.; Vandenplas, J.; Soares, A.C.C.; Sevillano, C.A.; Veroneze, R.; Pires, M.D.F.A.; De Freitas, C.; et al. Genome-wide association studies for tick resistance in *Bos taurus* × *Bos indicus* crossbred cattle: A deeper look into this intricate mechanism. *J. Dairy Sci.* **2018**, *101*, 11020–11032. [CrossRef] [PubMed]
17. Riggio, V.; Madder, M.; Labuschagne, M.; Callaby, R.; Zhao, R.; Djikeng, A.; Fourie, J.; Prendergast, J.G.; Morrison, L.J. Meta-analysis of heritability estimates and genome-wide association for tick-borne haemoparasites in African cattle. *Front. Genet.* **2023**, *14*, 1–10. [CrossRef]
18. Mapholi, N.O.; Maiwashe, A.; Matika, O.; Riggio, V.; Bishop, S.C.; Macneil, M.D.; Banga, C.; Taylor, J.; Dzama, K. Genome-wide association study of tick resistance in South African Nguni cattle. *Ticks Tick Borne Dis.* **2016**, *7*, 487–497. [CrossRef]
19. Jiang, J.; Ma, L.; Prakapenka, D.; Vanraden, P.M.; Cole, J.B.; Da, Y. A Large-Scale Genome-Wide Association Study in U. S. Holstein Cattle. *Front. Genet.* **2019**, *10*, 412. [CrossRef]
20. Johnsson, M. Genomics in animal breeding from the perspectives of matrices and molecules. *Hereditas* **2023**, *160*, 20. [CrossRef] [PubMed]
21. Valente, D.; Dutra, A.P.; Carolino, N.; Gomes, J.; Coelho, A.C.; Espadinha, P.; Pais, J.; Carolino, I. Prevalence and Risk Factors Associated with *Theileria annulata* Infection in Two Bovine Portuguese Autochthonous Breeds. *Pathogens* **2023**, *12*, 669. [CrossRef] [PubMed]
22. República D da. Portaria n.o 54-C/2023; Portugal. 2023, pp. 332-(75)–332-(146). Available online: https://files.dre.pt/1s/2023/02/04101/0007500146.pdf (accessed on 2 August 2023).
23. Rodrigues, F.T. *Estrutura Demográfica e Genética da Raça Bovina Alentejana*; Escola Superior Agrária de Santarém: Santarém, Portugal, 2021.
24. Carolino, N.; Vitorino, A.; Pais, J.; Henriques, N.; Silveira, M.; Vicente, A. Genetic Diversity in the Portuguese Mertolenga Cattle Breed Assessed by Pedigree Analysis. *Animals* **2020**, *10*, 1990. [CrossRef]
25. Santos, M.; Soares, R.; Costa, P.; Amaro, A.; Inácio, J.; Gomes, J. Revisiting the *Tams1*-encoding gene as a species-specific target for the molecular detection of *Theileria annulata* in bovine blood samples. *Ticks Tick Borne Dis.* **2013**, *4*, 72–77. [CrossRef]
26. Purcell, S.; Neale, B.; Todd-brown, K.; Thomas, L.; Ferreira, M.A.R.; Bender, D.; Maller, J.; Sklar, P.; De Bakker, P.I.; Daly, M.J.; et al. PLINK: A Tool Set for Whole-Genome Association and Population-Based Linkage Analyses. *Am. J. Hum. Genet.* **2007**, *81*, 559–575. [CrossRef] [PubMed]
27. Elsik, C.; Unni, D.; Diesh, C.; Tayal, A.; Emery, M.; Nguyen, H.; Darren, E. Bovine Genome Database: New tools for gleaning function from the *Bos taurus* genome. *Nucleic Acids Res.* **2016**, *44*, D834–D839. Available online: http://bovinemine-v16.rnet.missouri.edu:8080/bovinemine/begin.do (accessed on 30 July 2023). [CrossRef] [PubMed]
28. National Center for Biotechnology Information. National Library of Medicine. 2023. Available online: https://www.ncbi.nlm.nih.gov/ (accessed on 30 July 2023).
29. Cao, M.; Shi, L.; Peng, P.; Han, B.; Liu, L.; Lv, X.; Ma, Z.; Zhang, S.; Sun, D. Determination of genetic effects and functional SNPs of bovine *HTR1B* gene on milk fatty acid traits. *BMC Genom.* **2021**, *22*, 575. [CrossRef]
30. Kurz, J.P.; Yang, Z.; Weiss, R.B.; Wilson, D.J.; Rood, K.A.; Liu, G.E.; Wang, Z. A genome-wide association study for mastitis resistance in phenotypically well-characterized Holstein dairy cattle using a selective genotyping approach. *Immunogenetics* **2018**, *71*, 35–47. [CrossRef]
31. Sahana, G.; Guldbrandtsen, B.; Lund, M.S. Genome-wide association study for calving traits in Danish and Swedish Holstein cattle. *J. Dairy Sci.* **2011**, *94*, 479–486. [CrossRef]
32. Peters, S.O.; Kizilkaya, K.; Garrick, D.J.; Fernando, R.L.; Reecy, J.M.; Weber, R.L.; Silver, G.A.; Thomas, M.G. Bayesian genome-wide association analysis of growth and yearling ultrasound measures of carcass traits in Brangus heifers. *J. Anim. Sci.* **2012**, *90*, 3398–3409. [CrossRef]
33. Mateescu, R.G.; Garrick, D.J.; Reecy, J.M. Network Analysis Reveals Putative Genes Affecting Meat Quality in Angus Cattle. *Front. Genet.* **2017**, *8*, 171. [CrossRef]
34. Akanno, E.C.; Chen, L.; Ismail, M.K.A.; Crowley, J.J.; Wang, Z.; Li, C.; Basarab, J.A.; MacNeil, M.D.; Plastow, G.S. Genome-wide association scan for heterotic quantitative trait loci in multi-breed and crossbred beef cattle. *Genet. Sel. Evol.* **2018**, *50*, 48. [CrossRef] [PubMed]

35. Buitenhuis, B.; Poulsen, N.A.; Gebreyesus, G.; Larsen, L.B. Estimation of genetic parameters and detection of chromosomal regions affecting the major milk proteins and their post translational modifications in Danish Holstein and Danish Jersey cattle. *BMC Genet.* **2016**, *17*, 114. [CrossRef] [PubMed]
36. Meuwissen, T.; Hayes, B.; Macleod, I.; Goddard, M. Identification of Genomic Variants Causing Variation in Quantitative Traits: A Review. *Agriculture* **2022**, *12*, 1713. [CrossRef]
37. Mrode, R.; Ojango, J.M.K.; Okeyo, A.M.; Mwacharo, J.M. Genomic Selection and Use of Molecular Tools in Breeding Programs for Indigenous and Crossbred Cattle in Developing Countries: Current Status and Future Prospects. *Front. Genet.* **2019**, *9*, 694. [CrossRef] [PubMed]
38. Herbst, M.D.R.S. Review of epidermal growth factor receptor biology. *Int. J. Radiat. Oncol. Biol. Phys.* **2004**, *59*, 21–26. [CrossRef]
39. Kamouchi, M.; Philipp, S.; Flockerzi, V.; Wissenbach, U.; Mamin, A.; Raeymaekers, L.; Eggermont, J.; Droogmans, G.; Nilius, B. Properties of heterologously expressed hTRP3 channels in bovine pulmonary artery endothelial cells. *J. Physiol.* **1999**, *518*, 345–358. [CrossRef]
40. Simon, M.A.; Xu, A.; Ishikawa, H.O.; Irvine, K.D. Report Modulation of Fat:Dachsous Binding by the Cadherin Domain Kinase Four-Jointed. *Curr. Biol.* **2010**, *20*, 811–817. [CrossRef]
41. Noyes, H.; Brass, A.; Obara, I.; Anderson, S.; Archibald, A.L.; Bradley, D.G.; Fisher, P.; Freeman, A.; Gibson, J.; Gicheru, M.; et al. Genetic and expression analysis of cattle identifies candidate genes in pathways responding to *Trypanosoma congolense* infection. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 9304–9309. [CrossRef]
42. Soares-silva, M.; Diniz, F.F.; Gomes, G.N.; Bahia, D. The Mitogen-Activated Protein Kinase (MAPK) Pathway: Role in Immune Evasion by Trypanosomatids. *Front. Microbiol.* **2016**, *7*, 183. [CrossRef]
43. Lebedev, M.; Mceligot, H.A.; Mutua, V.N.; Walsh, P.; Chaigneau, F.R.C.; Gershwin, L.J. Analysis of lung transcriptome in calves infected with Bovine Respiratory Syncytial Virus and treated with antiviral and/or cyclooxygenase inhibitor. *PLoS ONE* **2021**, *16*, e0246695. [CrossRef]
44. Tümer, K.Ç.; Kızıl, M. Circulatory cytokines during the piroplasm stage of natural *Theileria annulata* infection in cattle. *Parasite Immunol.* **2023**, *45*, e12973. [CrossRef]
45. Szyda, J.; Mielczarek, M.; Fr, M.; Minozzi, G.; Williams, J.L.; Wojdak-Maksymiec, K. The genetic background of clinical mastitis in Holstein- Friesian cattle. *Animal* **2019**, *13*, 2156–2163. [CrossRef] [PubMed]
46. Yang, N.; Hu, N.; Zhang, J.; Yi, J.; Wang, Z.; Wang, Y.; Wu, P.; Chen, C. bta-miR-2904 inhibits bovine viral diarrhea virus replication by targeting viral-infection-induced autophagy via ATG13. *Arch. Virol.* **2023**, *168*, 11. [CrossRef]
47. Vassilev, V.B.; Donis, R.O. Bovine viral diarrhea virus-induced apoptosis correlates with increased intracellular viral RNA accumulation. *Virus Res.* **2000**, *69*, 95–107. [CrossRef]
48. Chen, Q.; Qu, K.; Ma, Z.; Zhan, J.; Zhang, F.; Shen, J.; Ning, Q.; Jia, P.; Zhang, J.; Chen, N.; et al. Genome-Wide Association Study Identifies Genomic Loci Associated with Neurotransmitter Concentration in Cattle. *Front. Genet.* **2020**, *11*, 139. [CrossRef] [PubMed]
49. Frank, M.; Kemler, R. Protocadherins. *Curr. Opin. Cell Biol.* **2022**, *14*, 557–562. [CrossRef]
50. NCBI. OR1S8 Olfactory Receptor Family 1 Subfamily S Member 8 [Bos taurus (cattle)] National Library of Medicine. 2021. Available online: https://www.ncbi.nlm.nih.gov/gene/?term=107133203 (accessed on 30 July 2023).
51. Favia, M.; Gerbino, A.; Notario, E.; Tragni, V.; Sgobba, M.N.; Elena, M.; Dell'Aquila, M.E.; Pierri, C.L.; Guerra, L.; Ciani, E. The Non-Gastric H+/K+ ATPase (*ATP12A*) Is Expressed in Mammalian Spermatozoa. *Int. J. Mol. Sci.* **2022**, *23*, 1048. [CrossRef] [PubMed]
52. Duan, X.; An, B.; Du, L.; Chang, T.; Liang, M.; Yang, B.; Xu, L.; Zhang, L.; Li, J.; E, G.; et al. Genome-Wide Association Analysis of Growth Curve Parameters in Chinese Simmental Beef Cattle. *Animals* **2021**, *11*, 192. [CrossRef]
53. Han, X.; Møller, V.L.L.; Groote, E.; De Bojsen-møller, K.N.; Davey, J.; Henríquez-olguin, C.; Li, Z.; Knudsen, J.R.; Jensen, T.E.; Madsbad, S.; et al. Mechanisms involved in follistatin-induced hypertrophy and increased insulin action in skeletal muscle. *J. Cachexia Sarcopenia Muscle* **2019**, *10*, 1241–1257. [CrossRef]
54. Novianti, I. *Molecular Genetics of Cattle Muscularity*; University of Adelaide: Adelaide, SA, Australia, 2010.
55. Wang, H.; Zhang, L.; Cao, J.; Wu, M.; Ma, X.; Liu, Z. Genome-Wide Specific Selection in Three Domestic Sheep Breeds. *PLoS ONE* **2015**, *10*, 1–21. [CrossRef]
56. Lee, S.; Lee, D.; Lee, M.; Ryoo, S.; Seo, S.; Choi, I. Analysis of single nucleotide polymorphisms related to heifer fertility in Hanwoo (Korean cattle). *Anim. Biotechnol.* **2020**, *33*, 964–969. [CrossRef]
57. Xia, J.; Qi, X.; Wu, Y.; Zhu, B.; Xu, L.; Zhang, L.; Gao, X.; Chen, Y.; Li, J.; Gao, H. Genome-wide association study identifies loci and candidate genes for meat quality traits in Simmental beef cattle. *Mamm. Genome* **2016**, *27*, 246–255. [CrossRef] [PubMed]
58. Thyrion, L.; Portelli, J.; Raedt, R.; Glorieux, G.; Larsen, L.E.; Sprengers, M.; Van Lysebettens, W.; Carrette, E.; Delbeke, J.; Vonck, K.; et al. Disruption, but not overexpression of urate oxidase alters susceptibility to pentylenetetrazole- and pilocarpine-induced seizures in mice. *Epilepsia* **2016**, *57*, 146–150. [CrossRef] [PubMed]
59. Tuli, A.; Singla LDa Sharma, A.; Mandeep, S.B.; Filia, G.; Kaur, P. Molecular epidemiology, risk factors and hematochemical alterations induced by *Theileria annulata* in bovines of Punjab (India). *Acta Parasitol.* **2015**, *60*, 378–390. [CrossRef]
60. Kurima, K.; Ebrahim, S.; Pan, B.; Holt, J.R.; Griffith, A.J.; Kachar, B. TMC1 and TMC2 Localize at the Site of Mechanotransduction in Mammalian Inner Ear Hair Article TMC1 and TMC2 Localize at the Site of Mechanotransduction in Mammalian Inner Ear Hair Cell Stereocilia. *CellReports* **2015**, *12*, 1606–1617. [CrossRef]

61. Kurima, K.; Yang, Y.; Sorber, K.; Griffith, A.J. Characterization of the transmembrane channel-like (TMC) gene family: Functional clues from hearing loss and epidermodysplasia verruciformis. *Genomics* **2003**, *82*, 300–308. [CrossRef] [PubMed]
62. Reyna, S.; Trujano-Chavez, M.Z.; Gallegos-Sánchez, J.; Becerril-Pérez, M.; Cadena-Villegas, S.; Cortez-Romero, C. Detection of Candidate Genes Associated with Fecundity through Genome-Wide Selection Signatures of Katahdin Ewes. *Animals* **2023**, *13*, 272.
63. Malvisi, M.; Palazzo, F.; Morandi, N.; Lazzari, B.; Williams, J.L.; Pagnacco, G.; Minozzi, G. Responses of Bovine Innate Immunity to *Mycobacterium avium* subsp. *paratuberculosis* Infection Revealed by Changes in Gene Expression and Levels of MicroRNA. *PLoS ONE* **2016**, *11*, 1–23. [CrossRef]
64. Sanchez, M.P.; Ramayo-Caldas, Y.; Wolf, V.; Laithier, C.; Jabri, M.; Michenet, A.; Boussaha, M.; Taussat, S.; Fritz, S.; Delacroix-Buchet, A.; et al. Sequence-based GWAS, network and pathway analyses reveal genes co-associated with milk cheese—Making properties and milk composition in Montbéliarde cows. *Genet. Sel. Evol.* **2019**, *51*, 34. [CrossRef]
65. Rivera, R.M.; Goldkamp, A.K.; Patel, B.N.; Hagen, D.E.; Joel, E.; Moreno, S.; Li, Y.; Kim, C.N.; Miller, C.; Williams, F.; et al. Identification of large offspring syndrome during pregnancy through ultrasonography and maternal blood transcriptome analyses. *Sci. Rep.* **2022**, *12*, 10540. [CrossRef]
66. El-Raey, M.; Geshi, M.; Somfai, T.; Kaneda, M.; Hirako, M.; Abdel-Ghaffar, A.E.; Sosa, G.A.; El-Roos, M.E.A.; Nagai, T. Evidence of Melatonin Synthesis in the Cumulus Oocyte Complexes and its Role in Enhancing Oocyte Maturation In Vitro in Cattle. *Mol. Reprod. Dev.* **2011**, *78*, 250–262. [CrossRef] [PubMed]
67. Haegeman, A.; Williams, J.L.; Law, A.; Van Zeveren, A.; Peelman, L.J. Characterization and mapping of bovine dopamine receptors 1 and 5. *Anim. Genet.* **2003**, *34*, 290–293. [CrossRef] [PubMed]
68. Juszczuk-Kubiak, E.; Flisikowski, K.; Wicinska, K. Nucleotide sequence and variations of the bovine *myocyte enhancer factor 2C* (*MEF2C*) gene promoter in *Bos taurus* cattle. *Mol. Biol. Rep.* **2011**, *38*, 1269–1276. [CrossRef] [PubMed]
69. Juszczuk-kubiak, E.; Wicinska, K.; Starzynski, R.R. Postnatal expression patterns and polymorphism analysis of the bovine *myocyte enhancer factor 2C* (*Mef2C*) gene. *Meat Sci.* **2014**, *98*, 753–758. [CrossRef]
70. Ahlawat, S.; Choudhary, V.; Kaur, R.; Arora, R.; Sharma, R.; Chhabra, P.; Kumar, A.; Kaur, M. Unraveling the genetic mechanisms governing the host response to bovine anaplasmosis. *Gene* **2023**, *877*, 147532. [CrossRef]