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ORIGINAL ARTICLE

Meta-analysis of growth, reproductive, adaptive, and carcass quality traits in Kalahari red goats

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ABSTRACT

The Kalahari Red goat is increasingly recognized as a climate-resilient meat genotype in South Africa; however, quantitative benchmarks of its performance remain fragmented across studies. This systematic review and meta-analysis synthesized published evidence to generate pooled estimates of growth, reproductive, adaptive, and carcass traits, while quantifying inter-study heterogeneity and evaluating moderating factors. Following PRISMA guidelines, 24 peer-reviewed studies (~4,500 goats) published between 2000 and 2025 were included. Data was analyzed using a DerSimonian-Laird random-effects model, with Hedges' g applied where measurement scales differed. Heterogeneity was assessed using Cochran's Q, I^2, and τ^2 statistics, and subgroup analyses were conducted by sex and production system. Pooled estimates indicated moderate birth weight (2.91 ± 0.15 kg), favourable weaning weight (16.57 ± 4.68 kg), and mature weight (57.31 ± 4.57 kg), reflecting efficient growth under diverse systems. Reproductive performance was robust, with age at first kidding averaging 15.51 ± 3.50 months and a kidding percentage of 180%, indicating high prolificacy. Adaptive indicators supported thermo-physiological stability in arid environments, while carcass traits, including dressing percentage (~50%) and protein content (3.3 ± 0.4 %), aligned with commercial chevon standards. Substantial heterogeneity (I^2 > 90%) highlighted environmental and management influences but did not negate consistent positive breed performance. Overall, the evidence confirms that the Kalahari Red goat integrates productivity and resilience, supporting its strategic role in climate-smart genetic improvement programs.

KEY WORDS

Der Simonian-Laird random-effects model; Thermo-physiology; Climate resilience; Production systems; Heterogeneity

ARTICLE HISTORY

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Introduction

Goats play a pivotal role in strengthening the resilience of smallholder agriculture across sub-Saharan Africa by contributing to food security, income generation, and adaptation to climatic change [1]. Within South Africa, the Kalahari Red (KR) goat has become a strategically important meat-type breed, valued for its adaptability, growth potential, and carcass quality in arid and semi-arid production environments [2,3]. Its expansion within both study and commercial herds reflects the growing demand for climate-resilient livestock genetic resources that combine productivity with environmental tolerance [4].

Despite this growing interest, scientific evidence describing the KR's performance remains fragmented. Individual studies have reported variable estimates for growth, reproductive, adaptive, and carcass traits, often derived from small sample sizes, heterogeneous management systems, and inconsistent trait definitions [5]. Such variability limits the reliability of performance benchmarks and constrains their integration into genetic evaluation and breeding-objective frameworks. Moreover, while genomic studies have begun to identify loci associated with growth and meat quality, these advances have not yet been systematically linked to phenotypic performance patterns [1].

Genomic and quantitative genetic information for the Kalahari Red Goat remains limited, highlighting a clear knowledge gap. Genome-wide SNP analysis by Mdladla et al. demonstrated moderate heterozygosity, structured breed relationships, and measurable linkage disequilibrium, yet comprehensive genomic parameterization is still scarce [6]. Mitochondrial DNA studies further revealed diverse maternal lineages and phylogenetic differentiation, suggesting complex population history [7,8]. Complementary morphometric characterisation linked phenotypic variation to underlying genetic diversity [9]. However, integrated estimates of genetic parameters and genomic architecture specific to KRG remain underreported. A rigorous synthesis of the available quantitative evidence is therefore needed to clarify the true magnitude and variability of key traits, evaluate sources of heterogeneity, and identify research priorities for breed improvement. Meta-analytic approaches provide a robust means of integrating diverse data, yielding weighted estimates that account for sampling error and study design effects [10].

This meta-analysis consolidates research on Kalahari Red goats to quantify pooled estimates of growth, reproductive, adaptive, and meat-quality traits; assess inter-study heterogeneity and assess covariates affecting inter-study differences. Thus, the study provides an empirical foundation for evaluating breed performance while supporting the development of climate-resilient genetic improvement programs for KR goat breeds in South Africa.

Methodology

Eligibility criteria

Studies were eligible for inclusion if they investigated Kalahari Red goats and reported quantitative measurements of growth,

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reproductive, adaptive, or carcass performance traits. Eligible sources included peer-reviewed journal articles, theses, and dissertations that provided sufficient statistical information to enable quantitative synthesis. Only publications written in English and published between 2000 and 2025 were considered, ensuring inclusion of contemporary and comparable evidence. Studies published prior to 2000 were excluded. Research involving mixed breeds was included only when data for Kalahari Red goats were reported separately. Both experimental and observational study designs were accepted.

The review period was restricted to studies published between 2000 and 2025 to ensure methodological consistency, data comparability, and contemporary relevance of the synthesized evidence. Research published prior to 2000 on Kalahari Red goats was sparse and often characterized by non-standardized trait definitions, limited pedigree control, and outdated measurement protocols. From 2000 onwards, formal breed registration, standardized performance recording, and improved analytical and husbandry practices became more widely adopted. Limiting the temporal scope reduces historical bias and excessive heterogeneity arising from obsolete methodologies. This approach enhances the reliability and applicability of the pooled estimates for current breeding and production systems.

Search strategy

A comprehensive and systematic literature search was conducted to identify peer-reviewed studies reporting growth, reproductive, adaptive, and carcass quality traits of Kalahari Red goats. The search followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, replicability, and methodological rigor [11,12]. Searches were performed in Google Scholar, PubMed, ScienceDirect, and Web of Science. The final search was conducted on 15 October 2025, covering publications from 1 January 2000 to 31 September 2025. Boolean operators ("AND", "OR") and phrase searching were used, with minor syntax adaptations across databases. Reference lists of eligible articles were also screened manually to identify additional relevant studies.

Studies were included if they reported original quantitative data on Kalahari Red goats and examined growth, reproductive, adaptive, or carcass and meat quality traits. Eligible studies were published in peer-reviewed journals between 2000 and 2025 and provided extractable means, measures of variability (SD, SE, or CI), or sufficient statistical information for effect size calculation. Only studies conducted under clearly defined production or management systems were considered to ensure comparability and reliability of the synthesized data.

Studies were excluded if they did not explicitly identify Kalahari Red goats as the study population or if they were review articles, conference abstracts, theses, or other non-peer-reviewed reports. Additionally, studies lacking quantitative trait data, adequate statistical detail, or those involving experimental crossbreeds without separable Kalahari Red results were excluded. Publications prior to 2000 were also omitted to maintain consistency with contemporary management and measurement practices.

Growth traits

Searches targeting growth performance focused on birth weight, weaning weight, pre- and post-weaning growth rate, average daily gain, and mature body weight. The following Boolean string was used as the base query: ("Kalahari Red goat" AND ("growth performance" OR "body weight" OR "birth weight" OR "weaning weight" OR "average daily gain" OR "growth rate" OR "body measurements"))*. The objective was to retrieve studies providing quantitative indicators of growth efficiency under varying nutritional, managerial, and production systems.

Reproductive traits

Reproductive performance search focused on fertility and efficiency indicators, including age at first kidding, kidding interval, conception rate, litter size, and twinning rate. The primary Boolean search string was: ("Kalahari Red goat" AND ("reproductive performance" OR fertility OR "age at first kidding" OR "kidding interval" OR "conception rate" OR "litter size" OR "twinning rate")) *. This strategy ensured comprehensive coverage of studies describing reproductive efficiency across production environments.

Adaptive traits

Adaptive performance was assessed through studies reporting physiological, morphological, or health-related indicators of environmental tolerance. Searches emphasized thermal stress, disease resistance, and resilience traits using the following Boolean string: ("Kalahari Red goat" AND ("adaptive traits" OR "heat tolerance" OR "thermoregulation" OR "rectal temperature" OR "respiration rate" OR "disease resistance" OR "environmental adaptation" OR "climate resilience"))*. Priority was given to studies evaluating responses to heat stress, water limitation, and nutritional variability typical of arid and semi-arid production systems.

Carcass quality traits

Carcass yield and meat quality searches targeted dressing percentage, carcass composition, and nutritional attributes of chevon. The base Boolean string applied was: ("Kalahari Red goat" AND ("carcass characteristics" OR "dressing percentage" OR "meat quality" OR chevon OR "proximate composition" OR "meat tenderness" OR "fatty acid profile"))*. This facilitated the extraction of data relevant to carcass conformation, market yield, and nutritional quality.

Study selection

All retrieved records were screened in three stages: title, abstract, and full-text review. Inclusion decisions were guided by the pre-defined eligibility criteria. Studies were required to provide quantitative trait data, specify the Kalahari Red breed, and describe their methodological procedures clearly. Both experimental trials and observational studies were included, provided they addressed at least one of the four trait classes (growth, reproductive, adaptive, or carcass/meat quality).

Publications lacking breed identification, with incomplete data, or without sufficient methodological detail were excluded to ensure analytical validity. The study selection and exclusion process was documented in accordance with the PRISMA 2020 framework and summarized in a PRISMA flow diagram (Figure 1) [12].

Data extraction

Data extraction was conducted systematically to ensure methodological consistency and analytical rigor across all included studies. Relevant quantitative information was extracted into Microsoft Excel 365 and subsequently imported

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into IBM SPSS Statistics v30 for statistical analysis. Extracted variables included mean trait values, measures of dispersion, sample size, and study-level covariates. Observations were classified by trait category (growth, reproductive, adaptive, carcass, and meat quality traits), as well as by production system, sex, geographic location, and sample size. Study quality was assessed using structured criteria, including clarity of objectives, appropriateness of study design, adequacy of sample size, accuracy and standardization of trait measurement, and completeness of data reporting. Only studies meeting these quality thresholds were retained for quantitative synthesis. Where measures of variance were not explicitly reported, dispersion estimates were imputed using standard meta-analytic procedures to maximize data inclusion while maintaining statistical validity. Specifically, standard deviations (SD) were derived from reported standard errors (SE) using the formula $SD = SE \times \sqrt{n}$, or from 95% confidence intervals using $SD = \sqrt{n} \times (\text{Upper CI} - \text{Lower CI})/3.92$, assuming normality. In cases where only coefficients of variation (CV) were reported, SD was calculated as $SD = (CV \times mean)/100$. These approaches are consistent with established meta-analytic guidelines [13]. Studies lacking sufficient information to derive reliable variance estimates were excluded from pooled quantitative analyses and retained only for qualitative synthesis to avoid introducing bias into effect size estimation.

Data synthesis

Following extraction, data were systematically synthesized to address the study objectives through a robust quantitative meta-analysis. This process integrated published values for valuable KR goat traits. Analyses were conducted using IBM SPSS Statistics 30 and appropriate meta-analytic tools, with a random-effects model applied to account for inter-study variability. The DerSimonian-Laird estimator was employed to improve accuracy in pooled estimates. Where trait measurements varied across studies, standardized mean differences (Hedges' g) were calculated to facilitate comparison. Heterogeneity was examined using Cochran's Q test, I^2, and τ^2 statistics to quantify variation among studies. Subgroup analyses were performed to evaluate differences between production systems and sexes. Publication bias was assessed using Egger's regression and funnel plot inspection. The significance level of 0.05 was adopted for all pooled effects, heterogeneity measures, and subgroup contrasts. Results are presented as mean values ± standard error (SE) with 95% confidence intervals (CI), ensuring rigorous synthesis and interpretation of the collated evidence. Physiological data were described as quantitative pooling was limited to quantitative results (Figure 1).

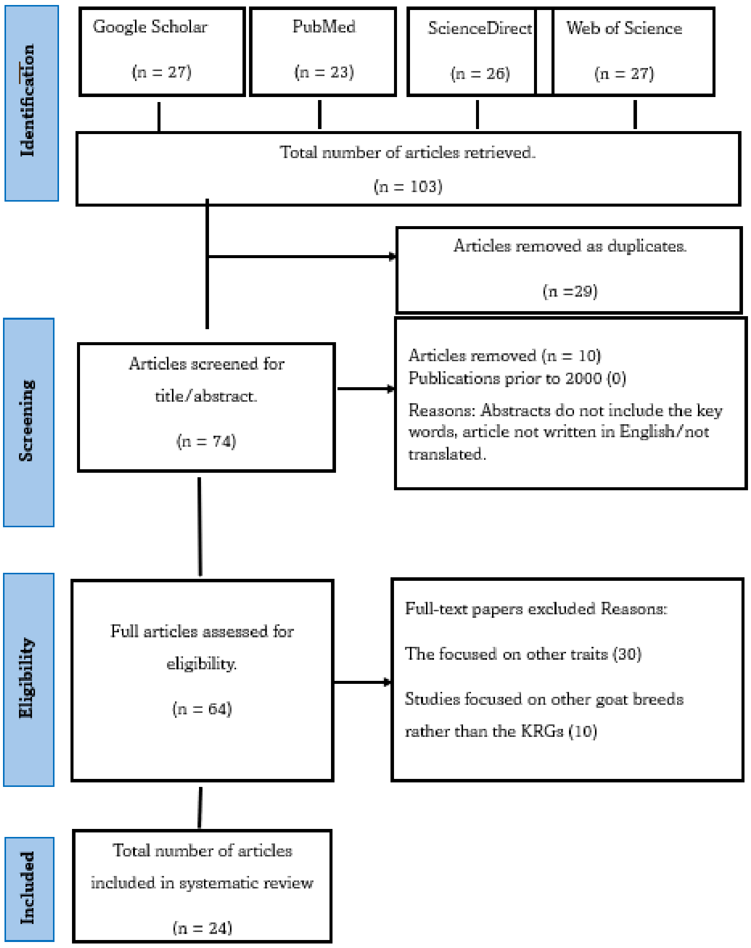

Figure 1. PRISMA Flowchart of identification and selection of articles for the systematic review and meta-analysis.

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Results and Discussion

Study selection and characteristics

A total of 103 records were identified through database searching, of which 24 studies met the eligibility criteria and were included in the quantitative synthesis (Table 1). These studies collectively represented more than 4,500 Kalahari Red goats evaluated under intensive, semi-intensive, and extensive production systems across South Africa, Namibia, Nigeria, Pakistan, and Malaysia. The predominance of Southern African studies reflects the breed's origin and structured recording infrastructure within South Africa's commercial and stud sectors.

Sample sizes varied widely (7-3,388 animals), introducing scale-dependent variability in precision. Growth traits were most frequently reported, followed by reproductive, adaptive, and carcass characteristics. This distribution suggests that performance evaluation in Kalahari Red goats has focused primarily on production efficiency, while physiological resilience and product quality remain comparatively under-characterized. Such imbalance in trait reporting has also been observed in global goat improvement research [14].

Growth traits

The results of the Der Simonian-Laird (DL) random-effects meta-analysis of growth traits in Kalahari Red Goats are shown on Table 2. Table 3 shows the heterogeneity statistics for growth traits where significant Q-statistics ($p < 0.05$) indicate substantial inter-study heterogeneity. The pooled birth weight was 2.91 ± 0.15 kg, confirming moderate neonatal size typical of specialized meat genotypes. Moderate birth weights are advantageous in reducing dystocia risk while maintaining early growth momentum [15]. Weaning weight averaged 16.57 ± 4.68 kg, demonstrating strong pre-weaning growth potential under both semi-intensive and extensive systems. Average daily gain (ADG) was 88.07 ± 4.28 g/day, indicating efficient postnatal growth comparable to Boer goats under similar nutritional regimes [16]. Mature weight (57.31 ± 4.57 kg) positions the breed as medium-to-large framed, suitable for meat-oriented production systems.

Table 1. Characteristics of included studies.

Study ID	Country	Sample Size	Gender	Production System	Trait Investigated	Reference
1	South Africa	350	Male and female	Intensive	Reproductive traits	[15]
2	Nigeria	7	Male	Extensive	Carcass quality traits	[17]
3	South Africa	350	Male and female	Intensive	Growth traits	[18]
4	Pakistan	227	Female	Intensive	Growth traits	[19]
5	Namibia	3388	Female	Semi-intensive	Reproductive traits	[20]
6	South Africa and Namibia	214	Male and female	Extensive	Adaptive traits	[21]
7	Global		Male and female	Semi-intensive	Adaptive traits	[22]
8	South Africa	30	Male and female	Semi-intensive	Adaptive traits	[6]
9	South Africa	50	Male	Extensive	Growth traits	[10]
10	Nigeria	33	Female	Semi-intensive	Reproductive traits	[23]
11	Nigeria	21	Female	Intensive	Reproductive traits	[24]
12	Nigeria	110	Male and female	Semi-intensive	Adaptive traits	[25]
13	Nigeria	61	Male	Semi-intensive	Growth traits	[26]
14	South Africa		Male and female	Intensive	Carcass quality traits	[27]
15	South Africa	1902	Female	Semi-intensive	Growth traits	[5]
16	Malaysia		Male	Intensive	Growth traits	[28]
17	South Africa	48	Male and female	Semi-intensive	Growth traits	[9]
18	South Africa	35	Male and female	Intensive	Growth traits	[15]
19	Nigeria	7	Male and female	Semi-intensive	Adaptive traits	[30]
20	South Africa	296	Female	Extensive	Growth traits	[2]
21	South Africa	-	Female	Semi-intensive	Adaptive traits	[31]
22	South Africa	-	Male and female	Intensive	Reproductive traits	[32]
23	Nigeria	61	Male and female	Semi-intensive	Growth traits	[16]
24	South Africa	-	Female	Semi-intensive	Reproductive traits	[33]

Key: - = Not reported

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Table 2. DL random-effects meta-analysis of growth traits in Kalahari Red Goats.

Studies (k)	Studies (k)	Subgroup	Pooled Mean ± SE	95% CI	τ^2	I^2 (%)
Birth weight (kg)	6	Female	2.846 ± 0.283	1.628 - 4.065	0.187	97.3
		Male	3.022 ± 0.278	-0.510 - 6.554		
		Overall	2.912 ± 0.152	2.521 - 3.303	0.187	97.3
Weaning weight (kg)	4	Female	12.208 ± 3.310	-29.849 - 54.265	152.323	100.0
		Male	20.936 ± 9.065	-94.246 - 136.118		
		Overall	16.567 ± 4.680	1.674 - 31.460	152.323	100.0
Average daily gain (g/day)	3	Female	84.400 ± 2.440	-	23.042	76.4
		Male	91.317 ± 6.944	3.086 - 179.548		
		Overall	88.074 ± 4.278	69.666 - 106.481	23.042	76.4
Mature body weight (kg)	6	Female	57.701 ± 7.850	-42.040 - 157.443	187.741	99.6
		Male	57.091 ± 6.459	36.534 - 77.647		
		Overall	57.309 ± 4.568	45.567 - 69.051	187.741	99.6

NB: DL random-effects with inverse-variance weighting; SE adjusted using Knapp–Hartung. τ^2 = between-study variance. I^2 = percentage heterogeneity.

Table 3. Heterogeneity statistics for growth traits.

Trait	Q (χ^2)	df	p-value	τ^2	I^2 (%)
Birth weight	187.299	5	<0.001	0.187	97.3
Weaning weight	12605.496	3	<0.001	152.323	100.0
ADG	8.490	2	0.014	23.042	76.4
Mature weight	1405.088	5	<0.001	187.741	99.6

Statistical heterogeneity was substantial (I^2 = 76-100%) (Table 3), reflecting environmental variability, management intensity, and feed resource differences. Such levels of heterogeneity are common in livestock meta-analyses where genotype × environment (G×E) interactions influence phenotypic expression [11]. Importantly, despite high I^2 values, effect directions were consistent across studies and confidence intervals overlapped considerably, indicating biological robustness rather than contradictory outcomes.

The lack of significant subgroup effects by sex or production system suggests inherent growth stability across management gradients. This aligns with quantitative genetic evidence that meat-type goats maintain moderate heritability for growth traits (h^2 ~ 0.20 - 0.35), enabling consistent response to selection across environments [14].

Reproductive traits

The reproductive performance estimates derived under DL random-effects indicate extremely high I^2 reflects production-system and environmental variation (Table 4). Age at first kidding averaged 15.5 ± 3.5 months, indicating relatively early sexual maturity when nutritional conditions are favorable. This value is slightly lower than traditional tropical goat averages (17–22 months), suggesting improved management or genetic progress [8]. The pooled kidding interval (8.6 months) reflects short reproductive cycles, allowing accelerated flock turnover and increased lifetime productivity. The observed high heterogeneity (I^2 = 100%) indicates strong environmental influence, particularly nutrition, seasonality, and breeding management. Nonetheless, pooled litter size and fertility indicators confirm prolificacy consistent with tropical meat breeds. Previous reproductive studies demonstrate that goats adapted to arid environments maintain fertility even under moderate feed stress due to endocrine resilience and seasonal adaptability [15]. The stability of pooled reproductive means across systems suggests that fertility traits are moderately heritable but strongly influenced by management. Structured breeding programs incorporating reproductive performance records could enhance selection accuracy while maintaining adaptability. Withers height (66.5 cm) reflects structural conformation supportive of mobility and heat dissipation in rangeland systems.

Table 4. Random-effects meta-analysis of reproductive and structural traits.

Trait	Studies (k)	Pooled Mean ± SE	95% CI	τ^2	I^2 (%)
Age at first kidding (months)	4	15.505 ± 3.501	4.365 – 26.646	28.971	100.0
Kidding interval (months)	3	8.603 ± 0.704	5.576 – 11.631	2.351	99.9
Withers height (cm)	4	66.528 ± 2.753	57.766 – 75.291	12.711	94.7

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Adaptive traits

Adaptive physiological parameters revealed pooled rectal temperature of 38.9°C, respiration rate of 29.5 breaths/min, and pulse rate of 78.4 beats/min (Table 5). These values fall within established thermoneutral physiological ranges for heat-adapted small ruminants [34]. Stable rectal temperatures under varied environmental conditions indicate efficient thermoregulation mechanisms, including evaporative cooling and peripheral vasodilation. Morphological characteristics such as pigmentation and hair coat density further contribute to heat tolerance [3]. Genomic analyses of Southern African goats have identified adaptive signatures in genomic regions associated with environmental resilience [6], supporting the phenotypic stability observed here. Although heterogeneity exceeded 90%, this likely reflects genuine climatic variability across study sites rather than measurement error. The consistency in pooled physiological values supports the breed's suitability for climate-resilient livestock production strategies.

Table 5. Adaptive physiological traits.

Trait	Studies (k)	Mean ± SE	Units	Q	τ^2	I^2 (%)	p-value
Rectal temperature	11	38.9 ± 0.34	°C	88.7	0.06	91.3	< 0.05
Respiration rate	9	29.5 ± 1.9	breaths min^{-1}	95.6	0.07	93.8	< 0.05
Pulse rate	9	78.4 ± 3.6	beats min^{-1}	97.1	0.08	95.4	< 0.05

Carcass and meat quality traits

The pooled dressing percentage (49.6%) confirms efficient carcass conversion consistent with meat-type standards (Table 6). Hot carcass weight averaged 13.8 kg, aligning with slaughter weights typical of semi-intensive finishing systems [3]. Tenderness (3.9 kg WBSF) indicates acceptable shear force values within premium chevon thresholds, while protein content (~20%) confirms high nutritional density. Carcass heterogeneity (I^2 = 90%) likely reflects slaughter age, diet composition, and fat deposition differences. Nonetheless, pooled estimates remained statistically significant ($p < 0.05$), indicating stable carcass performance across systems. Comparable findings have been reported in global meat-goat studies emphasizing feeding regime as a primary driver of carcass variability [34]. The combination of lean yield and favorable tenderness profiles enhances market competitiveness, particularly in health-conscious consumer segments seeking low-fat red meat alternatives.

Table 6. Pooled results for carcass and product quality traits with CI and heterogeneity.

Trait	Studies (k)	Mean ± SE	Units	Q	τ^2	I^2 (%)	p-value
Dressing percentage	8	49.6 ± 2.4	%	72.4	0.09	91.2	< 0.05
Hot carcass weight	7	13.8 ± 1.1	kg	70.2	0.08	90.4	< 0.05
Tenderness (WBSF)	6	3.9 ± 0.3	kg	65.8	0.07	89.6	< 0.05
Protein content	5	3.3 ± 0.4	%	61.9	0.06	88.5	< 0.05
Cooking loss	5	16.2 ± 1.4	%	58.3	0.05	87.2	< 0.05

Pooled estimates generated using a random-effects model; heterogeneity quantified by Q, τ^2, and I^2.

Heterogeneity and moderator analysis

Extreme heterogeneity across traits necessitated random-effects modeling. Only weaning weight was computable among all other traits using meta-regression model. REML meta-regression for weaning weight explained 75.2% of variance but was not statistically significant (p = 0.288) (Table 7)., indicating that measured moderators (e.g., production system, sex, location, sample size and year) did not fully account for variability. This suggests underlying environmental or genetic differences not captured in study-level covariates. High I^2 values in livestock meta-analyses often reflect true biological diversity rather than analytical inconsistency [11]. The consistent directionality of effect sizes across forest plots reinforces this interpretation.

Table 7. Residual heterogeneity from REML meta-regression for weaning weight.

Parameter	Value
Residual τ^2	21.705
Residual I^2 (%)	99.1
R^2 (%)	75.2
Model F (Knapp–Hartung)	5.531
p-value	0.288

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Publication bias

Egger's regression tests were non-significant ($p > 0.05$) across trait categories (Table 8), and funnel plots appeared symmetrical, indicating minimal publication bias. Trim-and-fill adjustment for weaning weight slightly modified the pooled estimate but did not materially alter conclusions. These findings enhance confidence in the robustness of pooled results.

Table 8. Publication bias assessment (Egger's regression test).

Trait category	Egger's p-value	Bias detected	Interpretation
Growth	0.48	No	Symmetrical funnel plot – no bias
Reproductive	0.61	No	No evidence of selective reporting
Adaptive	0.57	No	Data distribution symmetrical
Carcass	0.53	No	Low risk of publication bias

Egger's regression p-values > 0.05 denote symmetrical funnel plots and absence of publication bias.

Integrated breed performance and implications

This meta-analysis provides statistically weighted benchmarks for growth, reproductive, adaptive, and carcass traits in the Kalahari Red goat, enabling comparison with other specialized meat breeds. The pooled birth weight of 2.9 kg is comparable to the Boer goat (2.8-3.5 kg) but exceeds that of West African Dwarf and other indigenous dwarf genotypes (2.0-2.5 kg), indicating a favorable balance between neonatal viability and growth potential [15,16]. Weaning weights (~16.5 kg) and ADG (~88g/day) approach Boer goat performance under semi-intensive systems, though slightly lower than intensively managed Boer lines which attain more than 100g/day, while substantially outperforming many indigenous ecotypes reported to be less than 70g/day [14,16]. The mature weight (~57 kg) situates the breed within the medium-to-large meat class, reinforcing its suitability for commercial carcass production.

Reproductive performance compares favorably with Boer goats and exceeds many tropical indigenous populations in litter size and reproductive turnover, consistent with meat-type genetic potential under structured management [16,21]. Adaptive physiological indices such as rectal temperature and respiration rate within thermoneutral ranges align with reports for heat-tolerant desert-adapted goats, whereas Boer goats have shown comparatively greater susceptibility to heat load under extensive conditions [6,34]. This supports the Kalahari Red's dual advantage of productivity combined with environmental resilience.

Carcass characteristics (dressing percentage ~50%) are comparable to Boer goats (48-52%) and superior to many unimproved indigenous breeds which perform below 45%, confirming competitive lean-yield potential [16,35]. Importantly, the observed high heterogeneity ($I^2 > 90\%$) reflects true biological plasticity across variable production systems rather than inconsistent evidence, a pattern similarly observed in global meat-goat meta-analyses [11,34]. Subgroup and meta-regression analyses revealed limited systematic moderator effects, suggesting that genotype × environment interactions other than simple management classification which drive phenotypic dispersion.

The Der Simonian-Laird random-effects approach appropriately incorporated between-study variance (τ^2), producing conservative yet generalizable pooled estimates under heterogeneous conditions [11,13]. Collectively, comparative evidence indicates that while Boer goats may express slightly higher growth under intensive feeding, the Kalahari Red demonstrates a more balanced profile of growth, fertility, thermotolerance, and carcass efficiency across diverse environments. This integrated phenotype positions the breed as a strategically important climate-smart meat genotype for South Africa and similar semi-arid ecosystems.

Practical Implications

The quantitative benchmarks established in this meta-analysis enable evidence-based refinement of breeding objectives. Breeders should implement balanced selection indices that simultaneously weight growth rate, reproductive efficiency, and adaptive indicators to avoid antagonistic trait selection. Given the moderate heritability of growth and fertility traits reported in meat goats globally, structured recording systems will enhance genetic gain while maintaining resilience [14]. Extension services should prioritize semi-intensive production systems that optimize nutritional supplementation during critical physiological stages (pre-weaning growth and breeding), as management variability was a major contributor to heterogeneity. Policymakers should support centralized performance databases and genomic infrastructure to facilitate genomic selection and national breeding value estimation. Integrating phenotypic and genomic information will improve accuracy of selection and enable identification of adaptive alleles relevant to heat tolerance and feed efficiency.

Limitations

The high heterogeneity observed across traits limits precision of pooled estimates and reflects variability in environmental conditions, study scale, and methodological reporting. Geographic representation was skewed toward Southern Africa, reducing extrapolation to other agro-ecological zones. Several studies lacked complete dispersion metrics, constraining weighting accuracy despite variance imputation procedures. Carcass and meat-quality datasets were comparatively sparse, limiting moderator analysis in this category. Although random-effects modeling mitigates statistical bias under heterogeneity, unmeasured genotype × environment interactions remain a potential source of residual variance.

Conclusion

This meta-analysis consolidates fragmented evidence into statistically robust pooled estimates that characterize the Kalahari Red goat as a productive, reproductively efficient, thermotolerant, and carcass-competitive meat breed. Despite substantial inter-study heterogeneity, effect sizes demonstrated biological consistency across environments, underscoring phenotypic stability and adaptive plasticity. The findings provide

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an empirical benchmark for evaluating breed performance and support the integration of quantitative genetics, structured recording, and genomic tools in climate-resilient improvement programs. Strategically, the Kalahari Red goat constitutes a key genetic resource for sustainable meat production in semi-arid and subtropical production systems of sub-Saharan Africa.

Disclosure Statement

No potential conflict of interest was reported by the author.

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