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Phenotypic plasticity in trait performance of common dairy goat breeds under diverse environments: a systematic review

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Introduction: Dairy goat genotypes thrive across a range of ecological systems, making phenotypic plasticity highly relevant under constant environmental fluctuations. Maintaining production efficiency has become a priority for sustainable farming. The study explored existing literature on phenotypic plasticity of dairy goat breeds in response to varying environmental conditions across the world.

Methods: Publication searches were conducted on Google Scholar, PubMed, ResearchGate, and ScienceDirect databases. Following the PRISMA guidelines, the systematic review explored articles published between 2004 and 2024 from thirty-three (33) studies.

Results: These studies extend across various agro-ecological zones, highlighting differences in trait adaptability among breeds such as Alpine, Toggenburg, Saanen, and indigenous goats. The results showed high-yielding breeds performed optimally in temperate environments but struggled under heat stress, showing reduced milk yield and escalated reproductive inefficiencies. Conversely, indigenous breeds demonstrated superior phenotypic plasticity, maintaining consistent growth and reproductive performance in tropical and semi-arid zones.

Discussion: These findings emphasize the importance of breed selection for environmental adaptability to sustain productivity in dairy goat farming. This review addresses phenotypic plasticity and trait variability in dairy goat breeds across diverse environments, with an emphasis on environmental adaptability and genotype-by-environment interactions.

KEYWORDS

adaptability, ecology, genotype, indigenous, selection

Highlights

- A systematic review and meta-analysis was conducted on dairy goat trait performance under diverse environments.
- Saanen and Alpine breeds adapted well in temperate regions under intensive management systems.
- Indigenous breeds showed better adaptability and resilience in arid and tropical zones.
- Phenotypic plasticity was observable on milk performance and reproduction efficiency, further explained by genotype × environment interactions.
- Selection of breed should therefore align with the environment.

1 Introduction

Phenotypic plasticity refers to an organism's ability to change its phenotype in response to environmental changes (Sommer, 2020; Kebede et al., 2022). It is a key factor influencing the adaptability of livestock to various environmental spaces. In the dairy goat industry, adaptability is essential to counteract the negative effects imposed by diverse environmental stressors, which may result in slower growth rates, reduced reproductive efficiency, decreased milk quality and quantity, low feed intake, and increased susceptibility to diseases (Nair et al., 2021; Rovelli et al., 2020). Such challenges can lead to considerable economic losses in the livestock sector, particularly for smallholder farmers with limited resources in harsh environmental conditions. In a world of constant environmental fluctuations, phenotypic plasticity is quite relevant, as it allows animals to cope with the many diverse ecological systems in which they are raised and ensures their survival (Nair et al., 2021; Rovelli et al., 2020).

Dairy goats thrive across a range of ecological systems (Pragna et al., 2018), from smallholder farms in arid, harsh climates and resource-scarce environments to large-scale commercial farms in temperate regions (Nair et al., 2021; Mutindi et al., 2022). Goats exhibit remarkable adaptability to various environmental stresses, including thermal fluctuations, water scarcity, and limited food resources (Nair et al., 2021; Kahi and Wasike, 2019). A review by Nair et al (Nair et al., 2021), who highlighted their unique characteristics, reported that goats have the ability to increase their upper limit of body temperature during high heat loads and decrease it during cold conditions with food scarcity, demonstrating thermal phenotypic plasticity. Additionally, goats can downregulate their metabolism during periods of feed scarcity, which helps them conserve energy (Nair et al., 2021; Pragna et al., 2018). These characteristics make goats particularly resilient in arid and semi-arid environments, highlighting their phenotypic plasticity in coping with challenges posed by climate change. However, the productivity of dairy goats is highly influenced by environmental components, which include nutritional plane, climate forces, and management practices, which can vary significantly across different agro-ecological regions (Kahi and Wasike, 2019; Sejian et al., 2021). These changes directly impact key performance traits such as milk production, reproductive efficiency, and growth rates (Nair et al., 2021; Rovelli et al., 2020). This eventually limits the improvement of the dairy goat industry (Kahi and Wasike, 2019).

Due to intensifying variability in climate conditions, dairy goat breeds that perform well under ideal conditions may struggle to maintain productivity in more challenging environments, particularly in the face of increasing climate variability (Sejian et al., 2021). Despite the known importance of environmental adaptability, understanding of how different dairy goat breeds exhibit phenotypic plasticity and their capacity to adjust performance traits in response to changing environmental conditions is essential. Some breeds are recognized for their resilience in harsh environments, while others excel in productivity but lack adaptability attributes (Sejian et al., 2021). As climate change continues to intensify and impact production, it becomes increasingly crucial to better understand performance traits and enhance the sustainability of dairy goat breeds. Therefore, the objective of this review is to conduct a thorough evaluation of existing literature to explain environmental conditions influencing dairy goat productivity across common dairy goat breeds. The study will attempt to understand how dairy goat breeds exhibit phenotypic plasticity in traits such as milk production, reproductive efficiency, growth, and health across varying environmental conditions. As a result, the study will provide dairy goat farmers with useful choices for selecting breeds that are profitable, productive, and adaptable to environmental conditions.

2 Materials and methods

2.1 Eligibility criteria

The review was eligibly complied with the Population, Intervention, Comparison, and Outcome (PICO) framework (Moher et al., 2009). This framework was depicted as: Population (P)- common dairy goat breeds, Intervention (I) - diverse environmental conditions, Comparison (C) - same breeds across different environments and different breeds under similar environmental conditions, Outcome (O) - trait performance in milk production, reproductive efficiency in response to environmental changes. Articles were considered eligible if they at least contained the phrases "phenotypic plasticity", "dairy goats", "environmental effects," "GxE interaction," "milk production," or "reproductive efficiency" in their title or abstract. Studies eligible for inclusion have examined at least one traits outcome. Studies focused on performance traits influenced by key environmental factors such as agro-ecological zones, climatic attributes, nutritional regimes, and management practices were included. Studies on genotype-by-environment interactions without reporting trait outcomes, or studies on general environmental effects unrelated to phenotypic plasticity, were deemed not eligible. The eligibility criteria were broadened to include studies that focused on common dairy goats (Saanen, Toggenburg, Alpine, Nubian, and Indigenous) in controlled and unchanging environments, as the farm location and study area have climatic attributes necessary to depict environmental effects on traits. Therefore, studies conducted in controlled environments but considering environmental attributes such as climate or geography were also included. Exclusion criteria focused on studies that neither assessed environmental influences nor mentioned common dairy goats or phenotypic plasticity.

2.2 Search strategy

The search strategy was structured to cover the core elements of the PICO framework, specifically focusing on phenotypic plasticity, common dairy goats, environmental factors, and performance traits. Therefore, researchers independently conducted publication searches on Google Scholar, PubMed, ResearchGate, and ScienceDirect databases from the 15th of October to the 31st of December 2024. The combination of ("phenotypic plasticity" OR "trait performance") AND ("dairy goats" OR "goat breeds" OR "Saanen" OR "Alpine" OR "Toggenburg" OR "Nubian" OR "British Alpine") AND ("climatic conditions" OR "production systems" OR "agro-ecological zones" OR "management practices") AND ("milk yield" OR "reproduction traits") was used as key terms.

2.3 Inclusion criteria

The review included articles published over a 20-year period, spanning from 2004 to 2024, in peer-reviewed journals and written in English.

2.4 Exclusion criteria

Articles were excluded if they focused on non-dairy goat breeds or other livestock species. Studies that did not specify which environmental condition the breed was exposed to were also excluded. Furthermore, studies that did not record trait outcomes in relation to environmental factors were excluded. Literature reviews, editorials, opinion pieces, and conference abstracts without study outcomes were excluded. Articles published before the year 2004, duplicated studies, and non-English studies were excluded. Studies without accessible full-text articles were excluded.

2.5 Data extraction

Data extraction was carried out by the authors utilizing a standardized structure to gather information from the citations and abstracts. The authors collaborated to address and ensure the accuracy and consistency of the data/information collected for the study and finally came to an agreement on all items extracted from the articles. Qualitative and quantitative information was collected from the revised eligible studies. The key information recorded included author(s), year of publication, country of study, dairy goat breeds, trait evaluated, environment, and sample size of the studies. "Milk production," "reproduction efficiency," "adaptive response," "behavioral response," and "growth performance" were used to define performance traits recorded. Reproductive traits (kidding interval (KI, months), age at first kidding (AFK, months), prolificacy, twinning rate/litter) and milk production traits (mean daily milk yield (DMY, liters/day), lactation yield (LY, liters), lactation length (LL, days)) were extracted from eligible studies.

2.6 Quality assessment

The risk of bias for each included study was assessed using a modified version of the Joanna Briggs Institute (JBI) Critical Appraisal Checklist (Ma et al., 2020) for observational studies. Eight domains were evaluated: breed identification, environmental exposure definition, validity of trait measurement, study design, sample representativeness, confounder control, statistical analysis, and outcome reporting. Each domain was scored as "Yes," "No," "Unclear," or "Not applicable." Studies were categorized as having low (7–8 Yes), moderate (5–6 Yes), or high (≤4 Yes) risk of bias.

3 Results

3.1 Study selection and screening process

A total of four hundred and thirteen (n=413) articles were initially identified through database searches and manual screening of reference lists. Fifteen (n= 15) articles were removed as duplicates; three-hundred and ninety-eight (n=398) unique articles remained. These articles were assessed based on the title and abstract, resulting in the exclusion of two hundred and twenty-five (n= 225) studies that did not meet the predefined eligibility criteria. A total of hundred and seventy-three (n= 173) full-text articles were assessed for eligibility, leading to the exclusion of one hundred and forty (n= 140) additional studies. Ultimately, thirty-three (n= 33) articles published between 2004 and 2024 were included in this systematic review. Figure 1. illustrates the flowchart of the identification and selection process for this systematic review, which follows the PRISMA guidelines.

3.2 Characteristics of studies included in the systematic review

Studies extend across multiple continents, including Africa, Europe, South America, and Asia, reflecting the global relevance of phenotypic plasticity in dairy goats covering a broad range of environments. The studies represent a wide range of agro-ecological zones, climates, nutrition, and management systems. These studies collectively examined the phenotypic responses of dairy goats across five continents and twenty-one countries, encompassing a broad spectrum of environmental conditions, breeds, and trait categories. The sample sizes ranged from as small as eight animals to as large as 52,805, reflecting both controlled experiments and large-scale population studies.

Breed-specific insights emerged from studies in temperate regions, where high-input and well-managed systems supported detailed evaluations of Saanen and Alpine goats. These breeds showed favorable behavioral response and milk production traits under optimal conditions, but also revealed their limited adaptability to warmer climates, as evident by reduced milk production during periods of heat stress (Gomes et al., 2018; Mezzetti et al., 2024).

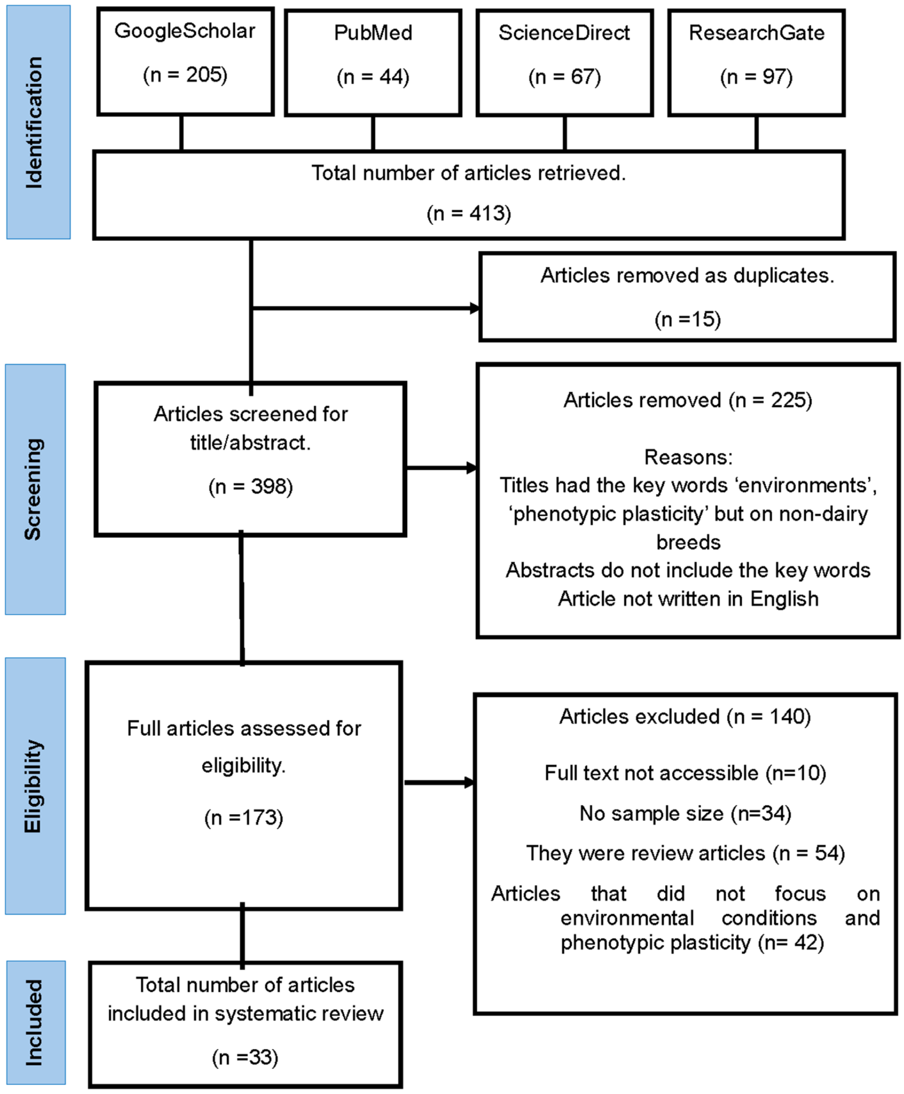

FIGURE 1
PRISMA flowchart of identification and selection of articles for the systematic review.

Studies on strip-grazing systems in high-quality temperate pastures and supplemented grazing regimes in sub-humid temperate environments further highlighted their responsiveness to management (Charpentier et al., 2019; Sainz-Ramírez et al., 2024). Multiple studies focused limitations of these high-yielding breeds in hotter climates, with heat stress leading to reduced milk production. In contrast, locally adapted breeds such as Alpine and Nubian goats showed stronger adaptability and phenotypic stability in the face of thermal stress when reared in semi-arid conditions in Sudan (Mahmoud and El Zubeir, 2024). This broad representation highlights the growing interest in assessing both commercial and local dairy goat breeds for their adaptability and phenotypic plasticity under diverse production environments. These studies provided detailed insights into how environmental factors like temperature and humidity influence specific performance traits, such as milk fat content and reproductive efficiency. The characteristics of studies used in the systematic review are presented in Table 1.

3.3 Publications per year and distribution of studies across geographical regions

A line graph representing the number of articles published per year is presented in Figure 2. The highest number of articles (n = 5) were published in 2022 and 2024, followed by (n = 4) in 2019 and 2020. Two articles were published in 2012, 2013, 2014, 2018, 2021, and 2023, respectively. One article was published in each of the following years: 2006, 2009, and 2010. No articles were published in 2004, 2005, 2007, 2008, 2011, and from 2015 to 2017. The distribution of studies across geographical regions is shown in Figure 3, highlighting research concentration in Europe and North America. The studies highlighted the diversity of environments in which dairy goat performance was evaluated. The studies originated from 21 countries, with the highest representation from Italy (n = 7), Spain (n = 6), Brazil (n = 3), Mexico (n = 3), and France (n = 3). Agro-ecological zones covered

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TABLE 1 Characteristics of eligible studies included in the review.

Authors	Year	Country	AEZ	Environments	Breeds studied	n	Performance trait(s)
Abdelkrim et al. (2023)	2023	France	Tropical	Nutrition	Lactating dairy goats	16	Milk performance
Adjassin et al. (2022)	2022	Benin	Humid	Heat stress (climate)	Saanen & Saanen × Red Maradi	103	Reproductive performance
Ali et al. (2023)	2023	Indonesia	Tropical	Heat stress (climate)/AEZ	Kacang, Kacang Etawah	12	Adaptive dynamics
Baenyi et al. (2021)	2021	DR Congo	Tropical	Unspecified	Indigenous goats	148	Milk & reproduction
Charpentier et al. (2019)	2019	France	Temperate	Strip-grazing (management), temperate (AEZ)	Alpine	36	Milk performance
Coloma-García et al. (2020a)	2020a	Spain	Temperate	Cold exposure (climate)	Murciano-Granadina	8	Adaptive dynamics
Coloma-García et al. (2020b)	2020b	Spain	Temperate	Heat stress (climate)	Murciano-Granadina	30	Behavioral response
Currò et al. (2019)	2019	Italy	Temperate	Management	Maltese, Mediterranean Red and Saanen	60	Milk performance
da Silva et al. (2024)	2024	Spain	Temperate	Temperate region (AEZ)	Majorera & Palmera breed	50	Adaptive dynamics
de Souza et al. (2014)	2013	Brazil	Tropical	Tropical (AEZ)	Saanen & Saanen* Anglo-Nubian	30	Adaptive dynamics
Ehrlenbruch et al. (2010)	2010	Norway	Temperate	Different roughages (nutrition)	Norwegian	8	Milk performance
Gindri et al. (2024)	2024	France	–	2-day Nutritional restriction	Alpine	72	Milk performance
Gomes et al. (2018)	2018	Brazil	Temperate	Enriched environment (management)	Saanen	12	Behavioral response
Grigoli et al. (2009)	2009	Italy	Mediterranean	Housed indoors and graze (nutrition and management)	Rossa Mediterranea goats	30	Milk performance
Kouri et al. (2019)	2019	Algeria	Arid	Arid conditions (AEZ)	Bedouin	13	Milk performance
Lallo et al. (2012)	2012	Trinidad	Tropical	Intensive system (Management)	Anglo-Nubian & British Saanen	160	Reproductive performance
Lévesque et al. (2022)	2022	Canada	–	Supplements (Nutrition)	Alpine	30	Milk performance
Magro et al. (2022)	2022	Italy	Temperate	Management	Saanen, Alpine & Murciano-Granadina	11 682	Milk performance
Mahmoud and El Zubeir (2024)	2024	Sudan	Semi-arid	Management	Nubian & Alpine	145	Reproduction and milk
Mellado et al. (2006)	2006	Mexico	Arid	intensive conditions in hot arid condition (management and AEZ)	Saanen, Toggenburg and French Alpine	4584	Reproductive performance
Menéndez-Buxadera et al. (2012)	2012	Spain	–	Heat stress (climatic conditions)	Murciano-Granadina and Payoya	15 954	Milk performance
Meza-Herrera et al. (2014)	2014	Mexico	Arid	Unspecified	Nubian, Granadian, Saanen, Toggenburg, Alpine	52 805	Reproductive performance
Mezzetti et al. (2024)	2024	Italy	Temperate	Dry-off (management)	Alpine & Saanen	28	Milk performance

(Continued)

TABLE 1 Continued

Authors	Year	Country	AEZ	Environments	Breeds studied	n	Performance trait(s)
Nascimento et al. (2022)	2022	Brazil	Semi-arid	Enrichment (management)	Saanen	12	Behavioral response
Rodríguez-Hernández et al. (2022)	2022	Spain	Mediterranean	Intensive and extensive (management)	Florida goats	19 772	Reproductive performance
Sainz-Ramírez et al. (2024)	2024	Mexico	Sub-humid Temperate	Grazing and supplements (management and nutrition)	Saanen	20	Milk performance
Salama et al. (2021)	2021	Spain	Temperate	Heat stress (climatic)	Murciano-Granadina	8	Behavioral response
Sandrucci et al. (2019)	2019	Italy	Temperate	Management	Local breeds, Saanen, Alpine	5 559	Milk performance
Singh and Sharma (2013)	2013	India	Semi-arid	Intensive and extensive production systems (management)	Jamunapari and Jakhrana	44	Milk performance
Steinshamn et al. (2014)	2014	Senja.	Mediterranean	Nutrition and climate	Norwegian goats	80	Milk performance
(Vacca et al. (2018)	2018	Italy	–	Production systems	Saanen, Alpine, Murciano, Granadina, Maltese,	1 272	Milk performance
Zhu et al. (2020)	2020	China	Temperate	Climate	Guanzhong dairy goats	149	Milk performance
Zucali et al. (2020)	2020	Italy	–	Management	Saanen and Alpine	200	Milk performance

included temperate zones (n = 15), particularly in Italy, reflecting the extensive dairy goat farming in this region; Tropical zones (n = 7); arid and semi-arid zones (n = 6), and Mediterranean zones (n = 3), and provided insights into goats' adaptability to moderate stress. Sub-humid temperate zones (n = 1), and lastly, unspecified agro-ecological zones (n = 5). This diversity allowed for a wide exploration of phenotypic plasticity under different environmental stressors and management systems.

3.4 Performance traits

The studies highlighted a diverse environmental impact on the performance traits of the dairy goat's breed. The performance traits evaluated in those studies included milk production (55%), reproductive efficiency (15%), adaptive response (12%), and behavioral response (12%), and milk + reproduction (6%) were significantly affected by climatic conditions, nutrition, and management practices. Two studies conducted in tropical and semi-arid regions (Adjassin et al., 2022; Nascimento et al., 2022) reported a decline in milk fat and protein content due to high temperatures during hot months. Saanen breeds, were reported to be sensitive to heat stress, exhibiting decreased daily milk yield compared to indigenous and crossbred goats. Studies from Brazil and Sudan (Nascimento et al., 2022; Mahmoud and El Zubeir, 2024) reported lower milk yield due to reduced feed quality and intake during dry seasons. Alpine and Saanen goats showed better performance in temperate climates but struggled in tropical and arid regions due to heat-induced metabolic stress (Gomes et al., 2018; Magro et al., 2022).

Indigenous breeds maintained their consistent growth rates and showed improved reproductive performance across the different environments, highlighting their phenotypic plasticity (Gomes et al., 2018; Magro et al., 2022). However, one article reported delayed reproduction cycles in dairy goat breeds not adapted to tropical climates, especially Alpine breeds (Nascimento et al., 2022). Studies demonstrated that dairy goats in arid regions adapted by increasing their upper critical temperature limits. Indigenous breeds displayed superior thermoregulation compared to high-yielding breeds like Saanen and Alpine (Mahmoud and El Zubeir, 2024). Crossbred Saanen and Saanen × Anglo-Nubian in tropical climates exhibited better adaptation to high temperatures, maintaining consistent growth rates and reproductive performance along with lower physiological stress compared to purebred Saanen goats (de Souza et al., 2014). Crossbred' goats showed better nutrient utilization (Ali et al., 2023). More studies on dairy goats under heat stress conditions reported a substantial reduction in milk yield due to high temperatures (Zhu et al., 2020; Salama et al., 2021). One study (Coloma-García et al., 2020b) reviewed the effects of cold temperatures on the physiological responses of lactating dairy goats.

Milk production traits varied across breeds and agro-ecological zones as shown in Table 2. The Saanen breed showed a high somatic cell count (SCC) and consistent milk composition in temperate regions, with fat, protein, and lactose contents of 3.03%, 3.33%, and 4.40%, respectively (Meza-Herrera et al., 2014). Alpine goats in the

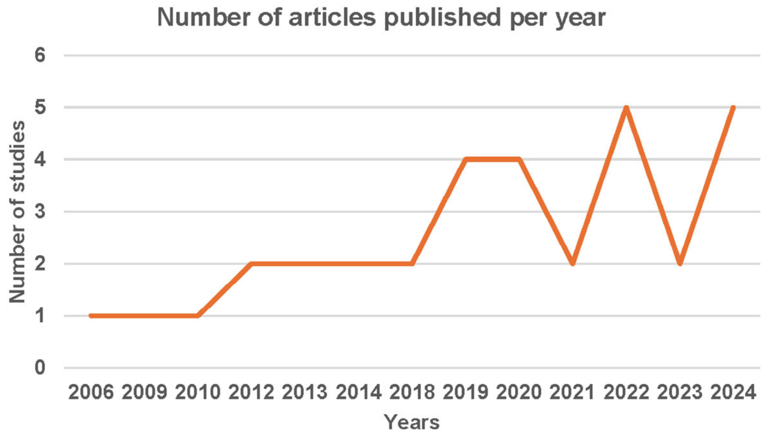

FIGURE 2
Publications per year on phenotypic trait performance in dairy goats (2004–2024).

same zone showed slightly higher fat and protein percentages of 3.77% and 3.56% respectively but slightly lower lactose (4.41%). Under semi-arid conditions, Alpine goats showed superior lactation performance with a longer lactation length (230 days) and higher lactation milk yield (3.89 kg) compared to Indigenous Nubian goats, which yielded 2.49 kg over a 150-day period (Mahmoud and El Zubeir, 2024). However, Nubians had markedly higher fat (4.82%) and lactose (4.78%) content, showing an adaptation favoring milk quality over quantity. Reproductive traits also showed clear variation across agro-ecological zones and breeds as shown in Table 3. In humid zones, Saanen goats had an early age at first kidding (AFK) of 12.48 months and a kidding interval (KI) of 13.63 months (Adjassin et al., 2022). Nubian goats in semi-arid conditions had a later AFK of 13.50 months and a longer mating interval (AFM) of 9.50 months (Mahmoud and El Zubeir, 2024). Twinning rates were highest among Nubian goats in tropical zones (1.86 kids/litter) (Magro et al., 2022) and in semi-arid regions (1.70), compared to Alpine goats (1.58–1.73) and Saanen (1.57–1.65) across arid and tropical agro-ecological zones.

3.5 Dairy goat breeds

A wide range of dairy goat breeds were evaluated under diverse environmental conditions. The Saanen breed was the most often studied, appearing in fourteen (14) studies, followed closely by the Alpine breed, which was included in eleven (11) studies. These two cosmopolitan breeds are commonly used in both commercial and

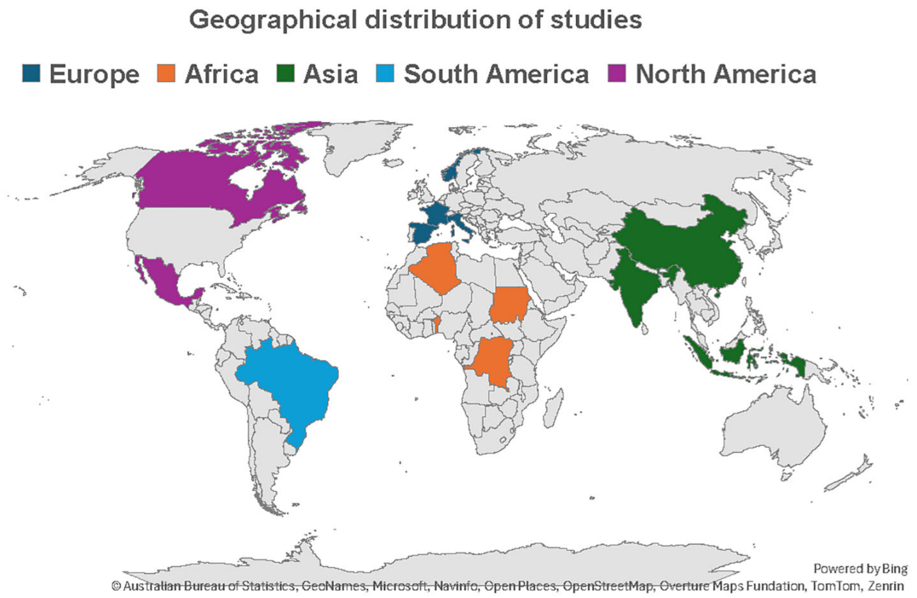

FIGURE 3
Global distribution of studies on dairy goat phenotypic traits across countries and agro-ecological zones.

smallholder dairy systems and were often assessed under temperate, semi-arid, and tropical climates. The Murciano-Granadina appeared in seven studies, primarily in Spain and Italy. Other notable breeds included the Nubian and Anglo-Nubian (n = 4), which were often studied in arid and tropical environments due to their heat tolerance, and the Norwegian dairy goat (n = 2), representing colder temperate systems. Indigenous breeds such as Florida, Majorera, Palmera, Payoya, Kacang, Kacang Etawah, and local Mediterranean breeds (e.g., Garganica, Girgentana, and Sarda) were also represented, though less often. Studies (n = 3) referred to goats as "lactating dairy goats" or "Indigenous" without specifying breed yet were included due to their relevance to trait-environment relationships.

4 Discussion

The results of this study demonstrate how environmental influences have a significant impact on dairy goat performance traits and how phenotypic plasticity shapes the goats' ability to adapt to a variety of ecological systems. The importance of phenotypic plasticity and genotype-by-environment (G × E) interactions in explaining specific responses to climatic stressors, nutritional regimes, and management systems was evident in this review. These findings are consistent with the increasing understanding that environmental adaptation is a key factor in determining dairy goat productivity.

4.1 Environmental impacts on trait performance

The reviewed studies demonstrated that milk production, reproductive efficiency, growth rates, and physiological responses in dairy goats are significantly affected by climatic conditions, nutritional availability, and management practices. The effect of environmental conditions on milk production in dairy goats includes the impact of seasonal factors, such as the month of kidding, which can influence milk yield. Goats kidding out-of-season (giving birth outside the expected breeding period) tend to produce slightly less milk than those kidding in-season. Moreover, practices such as breeding goats out of season and extending lactation periods can also affect the overall sustainability of goat milk production (Zucali et al., 2020). It was observed that primiparous goats produce milk with higher fat and protein content compared to multiparous goats (Sandrucci et al., 2019). This indicates that the lactation stage and the number of births can significantly affect the nutritional profile of the milk. The differences in milk production and quality among various breeds highlight the importance of genetic traits in these outcomes. The presence of both high-yielding specialized breeds and local breeds across different farms reflects the diversity in management practices and breeding strategies adopted by farmers. Environmental factors influencing key traits like milk production and reproductive efficiency, which are central to this review, were evaluated. Environmental conditions, like the hot climate of Sudan, affect not just the amount of milk goats produce but also its quality. Nubian goats, for instance, produced milk with a higher fat content, which is important for dairy production, while Alpine goats had lower fat percentages. This emphasizes how environmental factors like nutrition, heat, and management practices can shape performance traits in goats.

The discussion of environmental impact on traits will be based on the different (i) nutritional plane, (ii) climatic attributes in different regions, and (iii) management practices.

4.1.1 Nutritional plane

The nutritional impact was documented in temperate conditions. The dietary composition of dairy goats plays a significant role in influencing their water metabolism and overall milk production. The type and quality of feed, including the dry matter content, is a crucial environmental factor that directly affects key performance traits in dairy goats, such as water intake and milk production. The connection between high dry matter diets and increased water needs demonstrates how environmental factors like diet composition influence physiological processes and, consequently, performance traits. In environments where water availability may be limited, the high-water requirement associated with such diets could also become a limiting factor for productivity (Ehrlenbruch et al., 2010; Gindri et al., 2024). As physiological water stress can impair feed utilization and milk secretion. Thus, even in nutrient-rich systems, environmental constraints (like water availability) can act as secondary limiting factors. Conversely, goats in temperate regions benefit from more consistent and higher-quality forage, which supports optimal lactation and growth. Primiparous goats in temperate zones produced milk with higher fat and protein content compared to multiparous goats, largely due to the availability of energy-rich diets that supported higher metabolic activity (Abdelkrim et al., 2023). A trend likely driven by more efficient nutrient partitioning in younger animals and higher metabolic responsiveness during their first lactation. This emphasizes how both physiological stage and diet interact to shape trait expression, with nutrient-rich environments amplifying productive potential in genetically responsive individuals.

A study in the Mediterranean region, has shown that night-grazing results in higher milk yields compared to day grazing or indoor housing. Rossa Mediterranea goats that grazed at night produced more milk than those that grazed during the day or were housed indoors. Additionally, night grazing goats exhibited lower urea levels in their milk, indicating a more efficient utilization of dietary nitrogen, which is beneficial for milk quality (Koets et al., 2019). The physiological explanation lies in reduced thermal load during night-grazing, which conserves energy otherwise spent on thermoregulation. In addition, goats grazing at night exhibited lower urea concentrations in their milk, suggesting more efficient protein metabolism and improved dietary nitrogen utilization. This outcome points to an interaction between feeding time, thermal comfort, and metabolic pathways reinforcing the concept of phenotypic plasticity, where environmental effects shape internal physiological responses. The study on the effects of different forage

TABLE 2 Milk production performance of dairy goat breeds across agro-ecological zones.

Breed	AEZ	Milk production traits						Country	Reference
		LL (days)	LMY (kg)	Fat (%)	Protein (%)	Lactose (%)	SCC		
Saanen	Temperate	-	2.89 ± 0.04	3.03 ± 0.03	3.33 ± 0.02	4.40 ± 0.01	6.28 ± 0.07	Italy	Magro et al. (2022)
Indigenous (Nubian)	Semi-arid	150 ± 1.15	2.49 ± 0.83	4.82 ± 0.24	3.58 ± 0.08	4.78 ± 0.09	-	Sudan	Mahmoud and El Zubeir (2024)
Alpine	Semi-arid	230 ± 2.16	3.89 ± 0.38	3.55 ± 0.21	3.33 ± 0.07	4.54 ± 0.08	-	Sudan	Mahmoud and El Zubeir (2024)
	Temperate	-	2.46 ± 0.05	3.77 ± 0.04	3.56 ± 0.02	4.41 ± 0.01	6.02 ± 0.08	Italy	Magro et al. (2022)

1 AEZ, Agro-ecological zone; LL, Lactation length; LMY, Lactation milk yield; Fat (%) = milk fat percentage; Protein (%) = milk protein percentage; Lactose (%) = milk lactose percentage; SCC, Somatic cell count.

types and grazing seasons on the milk production and quality of Norwegian dairy goats was documented, comparing the effects of grazing on woodland rangeland versus cultivated pasture, as well as the differences between grazing and hay feeding (Steinshamn et al., 2014). These variations in forage type have been found to influence not only the quantity of milk produced but also the quality, particularly the fatty acid profiles present in the milk.

Goats grazing on woodland rangeland produced less milk but had higher fat and total solids content compared to those on cultivated pasture, with significant seasonal variations in milk yield and composition (Vacca et al., 2014). However, goats grazing on cultivated pastures produced more milk compared to those grazing on rangeland. This difference in milk yield was further explained by energy expenditure associated with locomotion on rangeland rather than differences in feed intake or herbage quality (Steinshamn et al., 2014). Thus, goats on rangeland expended more energy moving around, which negatively affected their overall milk production (Steinshamn et al., 2014). Strip-grazing on high-quality multispecies temperate pastures was shown to enhance milk yield and nitrogen efficiency in Alpine goats, demonstrating how forage quality and grazing design directly influence productivity under temperate conditions (Charpentier et al., 2019). The dense, diverse sward likely provided more consistent nutrient intake and supported better rumen fermentation dynamics. Supplemented

TABLE 3 Reproductive performance of dairy goat breeds across agro-ecological zones.

Breed	AEZ	Reproductive measures					Country	Reference
		AFK (months)	AFM (months)	KI (months)	Prolificacy	Twinning rate/litter		
Saanen	Humid	12.48 ± 0.93	-	13.63 ± 1.24	–	–	Brazil	Adjassin et al. (2022)
	Arid	-	–	–	–	1.57 ± 0.01	Mexico	Meza-Herrera et al. (2014)
	Tropical	-	–	–	1.65 ± 0.10	–	Trinidad	Lallo et al. (2012)
Toggenburg	Arid	-	-	-		1.66 ± 0.01	Mexico	Meza-Herrera et al. (2014)
Indigenous (Nubian)	Arid	-	-	-		1.77 ± 0.01	Mexico	Meza-Herrera et al. (2014)
	Tropical	-	8.54 ± 2.17	-	1.86 ± 0.07		Trinidad	Lallo et al. (2012)
	Semi-arid	13.50 ± 0.29	9.50 ± 0.17	8.50± 0.37		1.70 ± 0.61	Sudan	Mahmoud and El Zubeir (2024)
Alpine	Semi-arid	12.20 ± 0.51	17.30 ± 0.72	12.10 ± 0.16		1.73 ± 0.69	Sudan	Mahmoud and El Zubeir (2024)
	Arid	-	-	-		1.58 ± 0.01	Mexico	Meza-Herrera et al. (2014)

2 AEZ, Agro-ecological zone; AFK, Age at first kidding; AFM, Age at first mating; KI, Kidding interval.

grazing systems in sub-humid temperate zones allowed Saanen goats to maintain milk yield despite seasonal changes, highlighting the buffering effect of strategic feeding under fluctuating forage availability (Sainz-Ramírez et al., 2024). The combination of base forage and targeted feeding helps mitigate the negative effects of forage fluctuation, particularly during dry periods. Importantly, it also shows how the same breed can perform well in different conditions if nutritional stressors are appropriately managed, again reflecting environmental modulation of genetic potential. These studies show that nutrition is not a static input but a dynamic environmental condition that interacts with genotype, physiological stage, and system design. Goats exhibit remarkable flexibility in how they metabolize, utilize, and respond to feed inputs, and this flexibility is a central component of their phenotypic plasticity. However, the effectiveness of nutritional strategies depends on temperature, water, forage availability, and breed physiology.

4.1.2 Climatic attributes

Extreme heat stress conditions resulted in the lowest reproductive performances, including significant reductions in conception rates and prolificacy (Zucali et al., 2020; Adjassin et al., 2022). This aligns with findings from other literature indicating that climatic conditions can have detrimental effects on reproductive metrics in livestock. The reproductive system of goats is more sensitive to temperature fluctuations than other bodily systems. The environment significantly impacts reproductive performance in goats, particularly under heat stress conditions. In temperate climates, goats tend to produce higher milk yields due to milder temperatures and consistent feed availability. Saanen and Alpine goats kidding during spring, produced more milk than those goats bred outside the typical spring season, which is referred to as kidding out-of-season (Zucali et al., 2020). Kidding out-of-season, or during less favorable months, is associated with reduced milk yields due to a misalignment with natural breeding cycles and feed availability. Additionally, in temperate regions, the moderate climate allowed goats to experience longer lactation periods, better growth rates, and shorter kidding intervals (Mezzetti et al., 2024). This balance between favorable temperatures and adequate nutrition supports high productivity. However, when Alpine and Saanen goats were raised in tropical climates, their productivity declined due to heat stress, despite continuous lactation management being introduced to improve metabolic health (Adjassin et al., 2022). This demonstrates how seasonality directly affects lactation performance. Effects of adverse temperatures in humid regions, where temperatures are high year-round, the reproductive performance of crossbred goats was significantly lower than in cooler climates (Adjassin et al., 2022).

High ambient temperatures can adversely affect various reproductive parameters, including the growth of ovarian follicles, maturation of oocytes, and overall conception rates (Mahmoud and El Zubeir, 2024). This highlighted the sensitivity of the reproductive system to environmental stressors, particularly heat. Breeds with shorter kidding intervals and longer lactation periods may be more advantageous in certain climates, impacting herd productivity over time. Hot semi-arid regions pose a greater challenge due to high ambient temperatures and reduced forage quality. Heat stress has continuously been identified as a major factor limiting milk yield and reproductive efficiency. Elevated temperatures caused a decrease in milk production and negatively affected milk composition, including reductions in fat content, protein content, dry matter, and non-fat milk solids. It was found that heat stress during early pregnancy led to shorter gestation periods and altered exploratory behaviors in the offspring, particularly at one month of age (Zhu et al., 2020; Salama et al., 2021; Ali et al., 2023).

Goats exposed to cold temperatures produced less milk yield. However, the milk from cold temperatures was higher in quality. The milk contained increased levels of fat, protein, and lactose content. Indicating that while the quantity of milk may decrease in cold environments, the nutritional composition would still improve as a response to the metabolic adjustments made by the goats to cope with the cold. Moreover, goats exposed to cold mobilized body fat tissue, indicated by greater blood non-esterified fatty acids compared to goats in thermoneutral conditions (Coloma-García et al., 2020a; Coloma-García et al., 2020b).

4.1.3 Management practices

Continuous lactation has emerged as a management practice that may influence the metabolic health and milk production of dairy goats, particularly in Alpine and Saanen breeds (Mezzetti et al., 2024). The research findings indicated that Alpine and Saanen goats under continuous lactation exhibited notable metabolic health benefits. Continuously lactated goats demonstrated lower levels of haptoglobin and myeloperoxidase around kidding, with higher albumin and cholesterol levels. These findings suggest improved inflammatory condition and better energy availability, as evidenced by higher glucose levels. However, continuously lactating goats also showed a tendency towards higher somatic cell counts, which may indicate potential impacts on mammary gland health due to the continuous lactation process. The absence of a dry period mitigates inflammation, potentially enhancing energy balance despite increased body reserve mobilization prior to parturition (Menéndez-Buxadera et al., 2012).

Goat farming is primarily based on two production systems, the intensive and extensive systems. Intensive systems involve rearing goats indoors without grazing, while extensive systems allow goats to graze during spring and summer, with intensive management applied for the remainder of the year (Rodríguez-Hernández et al., 2022). While these systems may delay reproductive onset, they are often better aligned with local ecology and breed adaptability. For example, tropical and arid region breeds-maintained fertility under less predictable conditions, reflecting an evolved synchrony between genotype and management system (Menéndez-Buxadera et al., 2012). These two systems influence reproductive traits, such as age at first kidding (AFK) and kidding intervals (KI). Goats raised in intensive systems exhibit a shorter AFK compared to those in extensive systems. This trend suggests that the controlled environment and nutritional management in intensive systems may facilitate earlier maturation and breeding opportunities for young goats, thereby enhancing overall productivity (Zucali et al., 2020). KI is influenced by dry period, kidding season, lactation number, and kidding type; however, it did not vary by production system or kidding year period. Furthermore, performance across systems varies not only by intensity but also by breed responsiveness to those systems (Vacca et al., 2018).

The impact of environmental enrichment on the behavior and welfare of dairy goats in intensive housing is documented in this review. Environmental enrichment, although typically discussed in the context of animal welfare, can also be viewed as a management trigger of phenotypic plasticity. By modifying housing conditions to reduce thermal load through shaded areas, airflow enhancements, or object interaction. Enriched environments help goats express adaptive physiological and behavioral responses. The studies on Saanen goats demonstrated reduced respiratory rates and body temperatures under enriched conditions in heat-stress environments, alongside improved feed intake and natural behavior, thereby positively impacting productivity (Gomes et al., 2018; Nascimento et al., 2022). Thus, environmental enrichment contributed positively to the thermoregulatory responses of the goats, enhancing their well-being in hot environments. The enriched environments provided to the Saanen goats in the study are a form of environmental adaptation that directly impacts both welfare and productivity (Gomes et al., 2018; Nascimento et al., 2022). These responses reflect plastic adjustments to external stimuli, supporting the concept that environmental conditions, whether natural or managed, can influence the expression of performance traits. Thus, environmental enrichment serves not only as a welfare-enhancing tool but also as a management strategy that activates phenotypic plasticity. By allowing animals to respond to thermal and spatial stimuli, enrichment helps high-yielding breeds that are less robust to cope more effectively with environmental stressors in intensive systems.

4.2 Phenotypic plasticity and breed differences (breed adaptability)

Throughout the research, the idea of phenotypic plasticity, the ability of an organism to modify its characteristics in response to environmental changes, was clear. Significant differences exist in traits between breeds of dairy goats.

4.2.1 Indigenous breeds

Indigenous goat breeds consistently outperformed exotic breeds under harsh conditions, demonstrating superior adaptability. Reproductive performances, including the number of kidding per year and lactation length, varied significantly across different territories (Baenyi et al., 2021). The goats' ability to adapt to the mountain climate of South Kivu, characterized by temperature variations, suggested that they were well-suited to the local conditions, allowing them to maintain productivity despite environmental challenges. This suggests that environmental factors and local management practices may influence reproductive outcomes. The variability in milk yield, lactation period, and composition among breeds like Nubian and Alpine goats highlighted phenotypic plasticity. For example, the study showed that Nubian goats produce more milk than Alpine goats but have a shorter lactation period. The findings from Khartoum State emphasized how Nubian goats were better suited to arid and semi-arid regions categorized by environmental challenges, such as heat or resource scarcity, while also showing variability in traits like milk yield and lactation length (Mahmoud and El Zubeir, 2024). Such resilience contributes to the broader understanding of how goats adapt to different environmental and nutritional stressors. Several Mediterranean breeds, including Maltese and Girgentana, displayed moderate yield but stable composition under variable climates, indicating broader adaptability to management systems (Currò et al., 2019).

4.2.2 Saanen goats and Alpine goats

Saanen and Alpine displayed remarkable productivity under optimal conditions; their reduced adaptability limits their suitability for regions experiencing extreme climatic variability (Adjassin et al., 2022). This trade-off between productivity and adaptability underscores the need for breeding programs that prioritize traits enhancing resilience without compromising performance. The most widespread breeds, Saanen and Alpine, are recognized for their high productivity in Italy (Meza-Herrera et al., 2014; Sandrucci et al., 2019). Thus, they have been selected and managed to thrive in specific farming systems that emphasize milk yield. Additionally, the coexistence of both high-yielding specialized breeds and local breeds across various farms indicates that farmers have adapted their breeding strategies to suit different environmental conditions and production goals. Moreover, the seasonal breeding practices, where most dairy goats were bred during the natural estrus period, reflect an adaptation to the local climate and photoperiod, allowing for optimal milk production throughout the year. This adaptability is further supported by the variability in farming systems, ranging from intensive indoor to extensive outdoor systems, which cater to the specific needs of different breeds and their environments.

4.2.3 Crossbreeds

Crossbred goats exhibited better reproductive performance compared to Saanen goats under heat stress. This difference is attributed to the genetic traits of the crossbred goats, which are more adapted to warm climates, thus enhancing their reproductive capabilities in such environments. The breeds were adapted through a combination of management practices and environmental conditions (Adjassin et al., 2022). Crossbreeds have been shown to be more resilient and phenotypically flexible, making them better adapted to tropical climates and fluctuating seasonal conditions. The study examined key physiological parameters such as rectal temperature (RT), superficial temperature (ST), respiratory rate (RR), and heart rate (HR) to assess the responses of different goat breeds to seasonal change (de Souza et al., 2014; da Silva et al., 2024). It was found that ½S½AN goats exhibited lower levels of physiological stress compared to purebred Saanen goats in both the rainy and dry seasons. This was evident through consistently lower RT, RR, and HR in ½S½AN goats, indicating their superior adaptability to tropical climates. However, during the rainy season, higher temperature-humidity index (THI) values led to an increase in RT and respiratory rates for all breeds, signaling higher thermal discomfort and a greater risk of heat stress in this period.

The evaluation of adaptability using the adaptability coefficient (AC) revealed clear differences in thermal tolerance among breeds. Crossbred goats (½S½AN) exhibited intermediate AC values between their Saanen and Anglo-Nubian parent breeds, reflecting enhanced capacity to cope with heat stress. This suggests that crossbreeding can effectively combine the high productivity of specialized breeds like Saanen with the environmental resilience of more robust breeds such as Anglo-Nubian. Under humid tropical conditions, the Anglo-Nubian breed demonstrated superior thermoregulatory traits, higher prolificacy, and stable reproductive performance, reinforcing its suitability for tropical climates. Highlighting their phenotypic plasticity and ability to adapt to tropical climates, particularly under challenging conditions like the rainy season when thermal stress intensifies (Lallo et al., 2012). These findings suggest that the ½S½AN breed exhibits a higher degree of phenotypic plasticity and resilience, making them better suited for tropical environments and variable seasonal conditions. The study on Anglo-Nubian and Saanen breeds in the humid tropical environment of Trinidad indicated that the Anglo-Nubian breed is more suitable for this climate. The adaptation to the humid tropical environment was indicated by their superior thermoregulation, higher prolificacy, and comparable kidding intervals when compared to the Saanen breed (Lallo et al., 2012). These findings illustrate how genotype-by-environment interaction influences performance outcomes and emphasize the role of crossbreeding in expanding phenotypic plasticity. By buffering against climate-induced stressors, crossbred goats offer a promising solution for improving dairy goat resilience in heat-prone regions.

4.3 Genotype-by-environment interactions (G×E)

Genotype-by-environment (G × E) interaction describes the phenomenon where different genotypes respond differently to environmental conditions, resulting in variation in trait performance that cannot be explained by genetics or environment alone. Multiple studies clearly demonstrated G × E interactions in dairy goats raised under diverse agro-ecological and management systems. High-yielding breeds such as Saanen and Alpine demonstrated superior milk production in temperate climates under intensive management systems (Zucali et al., 2020; Magro et al., 2022). However, their performance consistently declined in tropical and arid zones, largely due to heat-induced metabolic stress, reduced feed intake, and lower adaptive capacity (Lallo et al., 2012; Adjassin et al., 2022; Mahmoud and El Zubeir, 2024). In contrast, indigenous breeds, such as Nubian and Bedouin goats, exhibited stable performance across a broader range of environmental conditions, particularly in hot and semi-arid regions (Meza-Herrera et al., 2014; Kouri et al., 2019; Baenyi et al., 2021). These breed-specific differences in performance across environmental conditions exemplify genotype-by-environment (G × E) interaction, where trait expression varies depending on the combination of genetic background and environmental condition a genotype is exposed to. Crossbred goats, such as ½Saanen×½Anglo-Nubian (½S½AN), further reinforce (G × E) interaction. Whereby, crossbreds showed lower physiological stress and better reproductive and thermoregulatory responses under the tropical zone compared to purebred Saanen goats (de Souza et al., 2014; Nascimento et al., 2022; Abdelkrim et al., 2023). Their adaptability coefficient values were intermediate between those of the Saanen and Anglo-Nubian breeds, demonstrating how hybrid genotypes can combine resilience and productivity through enhanced plasticity.

Genotype-by-environment interaction is essential for developing sustainable breeding programs that target specific agro-ecological zones. It challenges assumptions in breeding and policy that favor universal high-yielding breeds. Instead, it makes the case for environment-matched selection. Metabolic response patterns under nutritional restriction suggest that even within breeds, different genetic lines may vary in how they respond to short-term environmental challenges (Nascimento et al., 2022). Although these findings are not always explicitly analyzed as G × E, they support the broader principle that genotype and the environment interact to shape resilience, growth, milk yield, and reproductive efficiency. By recognizing that a goat's performance is only meaningful within an ecological context, G × E interaction reframes the goal of dairy breeding from maximizing absolute yield to optimizing stable and sustainable output under real-world conditions. Moreover, G × E is not limited to breed comparisons, it exists within breeds. Differences in energy recovery and metabolic resilience following nutritional challenges suggest that even within breeds, genotypes differ in environmental responsiveness. These intra-breed variabilities are critical for identifying robust animals suited for variable and climate-affected systems.

4.4 Strategies to mitigate environmental stressors

In regions with high temperatures, nocturnal grazing offers a practical way to reduce heat stress. By allowing goats to graze during cooler night hours, this strategy helps prevent overheating, leading to improved milk production and overall performance. Providing adequate shade and well-ventilated shelters is another key approach to reducing heat stress, particularly for goats that are housed or grazed during the day. Shaded and ventilated structures can significantly enhance thermal comfort and boost productivity. Ensuring efficient use of water is critical in areas facing water scarcity. Strategies such as optimizing water provision systems and ensuring access to clean water, especially for goats on dry matter diets, can help maintain hydration and support milk production. These findings emphasize breed-specific responses and water management strategies when evaluating the impacts of climatic attributes on goat performance. In cold climatic regions, dairy goats should be managed with caution. Avoiding exposure to sub-zero temperatures should be prioritized to prevent adverse negative impact on body condition and milk production. Furthermore, more research is obviously needed to determine what nutritional changes could help dairy goats survive in cold climates and how different cold temperatures and durations affect their metabolic reactions.

Although environmental enrichment has been studied in intensive systems, future research should explore how enrichment strategies can be applied in extensive systems where goats are exposed to natural elements and face challenges such as heat stress and limited forage. Understanding how these strategies can benefit goats in less controlled environments would expand their practical applicability. The review suggests that selecting the right breed and understanding how environmental factors affect goat performance are key to improving productivity and sustainability in dairy. An important aspect looked at is how metabolic response profiles can provide deeper insights into the adaptability of dairy goats to environmental challenges, particularly during periods of nutritional stress. There are distinct metabolic response patterns in lactating dairy goats when faced with nutritional challenges, showing that goats vary in how they respond and recover from these stressors (Abdelkrim et al., 2023). This variability in metabolic responses is significant in understanding resilience, a concept central to the discussion of phenotypic plasticity in dairy goats. Goats that exhibit more adaptive metabolic profiles are likely to cope better with environmental stressors, such as limited feed availability or poor nutrition, which are common in the environments covered in this review. This underlines the importance of looking at how goats manage stress on a physiological level, not just in terms of external performance traits like milk production.

4.5 Limitations and research gaps

This review found several limitations in existing literature. Many studies generalized findings across goat populations without distinguishing between dairy, meat, or mixed-purpose breeds. Most studies focused on high-yielding or well-known breeds such as Saanen, Alpine, and Nubian goats, leaving out lesser-known or local indigenous breeds that may exhibit greater adaptability to different environments. This bias towards popular breeds creates a gap in understanding how less-documented indigenous breeds might perform under environmental stress, limiting the generalizability of the findings. Additionally, the underrepresentation of studies focusing on specific regions, such as South Africa, limits the ability to draw comprehensive conclusions about local adaptation strategies. The limitation of this review is that although environmental enrichment is discussed, it does not fully fit within the broader focus of phenotypic plasticity and how goats adapt to different environmental conditions. Environmental enrichment, such as adding objects to improve animal welfare in intensive systems, can help reduce stress and improve performance. This does not fully cover how goats respond to more significant environmental challenges, such as heat or feed scarcity in extensive systems. While enrichment provides useful insights, it does not capture the full range of environmental factors that this review focuses on. The impact of heat stress in different environments and within different breeds has been overly studied with little to no exploration of cold environments. The results of heat stress are also similar. The scarcity of literature on the environmental impact evaluation of goat milk production has been noted by five articles in this review.

While performance traits remain the focus of most studies, a shift toward understanding resilience, especially metabolic, reproductive, and behavioral responses emerged across this systematic review. Goats that could maintain consistent physiological states, reproduce under seasonal pressure, or recover quickly after stress were consistently tied to resilient genotypes. Importantly, this resilience is often correlated with reduced input needs and stronger welfare outcomes for sustainability, not just productivity. This raised an important research and policy imperative, where selection goals must move beyond milk yield to include traits that confer environmental impacts. Breeds that may not top output charts under intensive management may offer more consistent returns under extensive systems. Indigenous breeds and crossbreds clarified this paradigm, even though they may be more adaptable to harsh climates and potentially have a lower environmental effect compared to high-yielding exotic breeds due to their ability to thrive with fewer resources. However, this aspect was not explored in detail.

5 Conclusion

The systematic review highlighted the critical role of phenotypic plasticity in dairy goat breeds, particularly examining the influence of environmental factors on dairy goat performance and highlighting the adaptability of various dairy goat breeds to varying environmental conditions in the world. Phenotypic plasticity was evident across all trait categories, with distinguishable genotype-by-environment interactions shaping performance trait expression. Common dairy goat breeds such as Saanen and Alpine excelled in temperate environments, while indigenous breeds like Nubian and local tropical goats showed superior resilience in arid and tropical conditions. There is a rise in research publications, particularly in 2022 and 2024, with a concentration on temperate regions such as Italy. The indigenous breeds showed better resilience to heat stress environments compared to high-yielding breeds. This adaptability may also correlate with a potentially lower input requirement, as these breeds can maintain productivity with fewer resources compared to high-yielding exotic breeds. The review suggests that selecting the optimum breed and understanding how environmental factors affect goat performance are key to improving productivity and sustainability in dairy farming. To further enhance the adaptability of goat breeds in tropical climates, it is essential to implement strategies that focus on developing breeds that are less sensitive to heat stress. Additionally, goat dairy farmers should monitor seasonal variations in the adaptive characteristics of their livestock to optimize management practices and improve productivity throughout the year. By prioritizing these strategies, the resilience of goat populations in tropical environments can be significantly improved. Future research should explore environmental enrichment strategies in extensive systems, where goats face natural elements and challenges. The study emphasizes the significant effects of climatic conditions, nutrition, and management practices on milk production, reproductive efficiency, and growth rates, advocating for breeding programs that prioritize resilient genotypes with high phenotypic plasticity. There is a need to align breed selection with specific agro-ecological zones to optimize productivity and enhance sustainability. To improve the adaptability and efficiency of dairy goat rearing globally. Further research is needed on underrepresented local breeds, especially in heat-stressed and resource-limited environments, alongside standardized trait reporting and environmental classification frameworks.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

OT: Conceptualization, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. PM: Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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