

Leveraging Indigenous Pig Genetic Resources for Climate-Resilient Breeding: Genomic Evidence, Functional Traits, and Future Directions

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ABSTRACT

Climate change is fundamentally reshaping the conditions under which global pig production operates, exposing the vulnerability of commercially selected genotypes that have been optimised for productivity at the expense of environmental robustness. In this context, climate resilience is understood as the capacity of an animal to maintain productive performance, reproductive stability, and physiological homeostasis across a range of environmental stressors, including heat load, disease challenge, and nutritional scarcity. Indigenous pig breeds distributed across Africa, Asia, and Latin America represent a largely untapped reservoir of this resilience, having evolved adaptive traits such as thermotolerance, immunocompetence, and metabolic flexibility through centuries of exposure to harsh and variable production environments. This review synthesises recent advances in high-throughput genomic approaches including genome-wide association studies, whole-genome resequencing, and functional transcriptomics to elucidate the molecular signatures underpinning these adaptive capacities, with particular attention to heat shock protein regulation, immune pathway plasticity, and genotype-by-environment interactions. Building on this genomic evidence, an integrated breeding framework is proposed that combines multi-trait selection indices, reaction norm modelling, and structured introgression of adaptive alleles into commercial lines, thereby reconciling productivity with resilience without undermining genetic gain. Key constraints, particularly the phenotyping gap and accelerating genetic erosion of local breeds, are critically examined alongside emerging opportunities in precision phenotyping and gene editing. Collectively, this review positions the strategic utilisation of indigenous pig genetic resources not merely as a conservation imperative but as a practical and urgent foundation for sustainable, climate-smart pig production in a warming world.

Keywords: Climate resilience; Indigenous pig breeds; Functional genomics; Heat stress; Genotype by environment interaction; Precision breeding; Genetic diversity; Thermotolerance.

INTRODUCTION

Global pig production plays a crucial role in food security and rural livelihoods, supporting over one billion animals worldwide (Adeschinwa et al., 2024) ^[1]. Although intensive production systems dominate in Asia, Europe, and the Americas, indigenous and smallholder pig systems remain essential to household income and nutrition across Africa and Latin America (Kim et al., 2024) ^[28]. However, the sector is increasingly affected by climate change, particularly through rising temperatures, more frequent heatwaves, and unstable feed resources (Llonch et al., 2024) ^[31]. Among these challenges, heat stress is especially critical, as it disrupts normal physiological processes, reduces growth performance, impairs reproduction, and ultimately threatens animal welfare and supply chain stability (Katiyar et al., 2025) ^[27].

A major challenge in modern pig breeding is the strong genotype-by-environment ($G \times E$) interaction, whereby high-performing commercial genotypes fail to express their full genetic potential under stressful conditions (Bussiman et al., 2025) ^[10]. Consequently, there is growing interest in the use of genomic technologies to identify the genetic basis of adaptive traits (Sinha et al., 2021) ^[56]. In this regard, indigenous pig breeds are particularly valuable, as long-term adaptation to local environments has endowed them with enhanced resilience and metabolic flexibility that commercial lines increasingly lack. Furthermore, the urgency of this challenge is

underscored by climate projections indicating that the frequency and severity of thermal and environmental stress events will continue to intensify across major pig-producing regions in the coming decades.

Despite this potential, indigenous genetic resources remain underutilised in mainstream breeding programmes. At the same time, the replacement of local breeds with industrial lines is accelerating genetic erosion, leading to the loss of unique adaptive alleles (Mathew and Mathew, 2023) ^[35]. This reduction in genetic diversity poses a serious risk to future climate-resilient breeding efforts and global food security (Pius et al., 2024) ^[44]. Therefore, bridging the gap between genomic research and practical breeding application is increasingly urgent.

In this review, climate resilience is defined as the capacity of an animal to maintain productive performance, reproductive stability, and physiological homeostasis across a range of environmental stressors, including heat load, disease challenge, and nutritional scarcity. The indigenous breeds examined are drawn primarily from Africa, Asia, and Latin America — regions where local pig populations have undergone centuries of natural and traditional selection under diverse and demanding environmental conditions. The genomic approaches considered include genome-wide association studies (GWAS), whole-genome resequencing, and functional transcriptomics, with a focus on the molecular signatures of thermotolerance, immune pathway plasticity, and genotype-by-environment interaction. Breeding applications discussed encompass multi-trait selection indices, reaction norm modelling, and structured introgression of adaptive alleles into commercial lines. Gene editing technologies such as CRISPR-Cas9 are acknowledged as an emerging frontier but are not the primary focus of this review. By synthesising genomic evidence with functional trait data and practical breeding frameworks, this paper provides a conceptual roadmap for harnessing indigenous pig genetic resources to strengthen the climate resilience of global pig production systems.

INDIGENOUS PIG BREEDS AS A GENETIC RESOURCE

Indigenous pig breeds represent a genetically distinct and largely untapped reservoir, offering significant potential for bolstering climate resilience within global porcine production (Pius et al., 2024) ^[44]. They are predominantly distributed across Africa, Asia, and Latin America and are typically maintained under low-input, smallholder management regimes (Osei-Amponsah and Kaumbata, 2025) ^[43]. In contrast to the high-intensity selection pressures applied to commercial lines, indigenous pigs have undergone centuries of natural and traditional selection under diverse environmental stressors, which has resulted in the retention of unique adaptive phenotypes (Yuan et al., 2025) ^[64]. Thus, these include superior thermotolerance, heightened immunocompetence, and high nutrient-utilisation efficiency under resource-scarce conditions (Adesogan et al., 2025) ^[2].

Recent advancements in genomic characterisation have elucidated the molecular basis of this resilience, revealing substantial allelic diversity that is often absent in cosmopolitan breeds (Zhang et al., 2023) ^[65]. Through the application of whole-genome sequencing (WGS), high-density SNP arrays, and haplotype mapping, researchers have identified specific genomic regions and candidate genes associated with heat shock response, pathogen resistance, and metabolic plasticity (Wang et al., 2024 ^[62]; Saadatabadi et al., 2023 ^[49]). These findings indicate that local populations harbour a suite of “resilience alleles” that could be strategically utilised to fortify commercial germplasm against climatic volatility. The current state of knowledge regarding these adaptive traits is summarised in Table 1.

Table 1: Key Adaptive Pillars of Indigenous Pig Genotypes

The following table summarises the primary adaptive advantages found in indigenous breeds that are critical for climate-resilient breeding:

Adaptive Trait	Functional Mechanism	Genomic Indicator
Thermotolerance	Enhanced heat dissipation and cellular protection (Zhong et al. 2023; Wen et al. 2024)	Heat Shock Proteins (e.g., <i>HSP70</i> , <i>HSF1</i>)
Nutritional Plasticity	Ability to maintain growth on high-fibre, low-protein diets (Škrlep et al. 2024; Liu et al. 2025).	Metabolic genes (e.g., <i>PPARA</i> , <i>LEP</i>)

Immunocompetence	Innate resistance to endemic tropical diseases (Frontiers in Vet Science, 2025).	MHC complex, Interleukins (e.g., <i>IL-6</i> , <i>TNF</i>)
Environmental Robustness	Consistent performance across varying environments (\$G \times \\$E\$) (Gilbert et al. 2025; Wen et al. 2024).	Epigenetic markers and regulatory SNPs

Table 2: Key Indigenous Pig Breeds and Their Adaptive Traits

Region	Breed	Heat Tolerance	Disease Resistance	Feed Efficiency	Reproductive Traits
Africa	Large White $\times$ Local	Moderate	High	Moderate	Good under low-input
Asia	Meishan	Moderate	High	High	High litter size
Latin America	Creole	High	Moderate	High	Good under low-input

Source: (Dotche et al., 2020; Suárez-Mesa et al., 2024; Zhou et al., 2021)

Nevertheless, the preservation of this genetic wealth is currently jeopardised by genetic erosion. The proliferation of industrial production models and unmanaged crossbreeding with exotic genotypes has led to the rapid dilution of locally adapted gene pools (Mathew and Mathew, 2023) ^[35]. This loss of biodiversity threatens not only cultural heritage but also the biological toolkit required for climate-smart breeding (Lu et al., 2025) ^[32]. Therefore, robust conservation initiatives are a prerequisite for any future breeding strategy aimed at maintaining long-term environmental robustness.

Moreover, the strategic introgression of adaptive alleles from indigenous pigs into commercial lineages offers a viable pathway for reconciling productivity with resilience (Mary et al., 2022) ^[34]. Bai and Plastow, (2022) ^[4] suggest that targeted crossbreeding, supported by genomic selection, allows for the transfer of heat tolerance and disease resistance traits without significantly compromising growth performance or carcass quality.

Ultimately, the value of these breeds extends beyond their current role in subsistence farming; they represent a critical biological insurance policy for the global livestock industry. Integrating the latent genetic potential of indigenous populations into the global breeding pyramid is therefore not merely an act of conservation but a strategic necessity to ensure the stability of animal protein production in an increasingly warming and unpredictable world.

GENOMIC TOOLS AND STRATEGIES FOR CLIMATE RESILIENCE

The rapid evolution of genomic technologies has fundamentally redefined the trajectory of porcine breeding, thereby providing a robust framework for identifying and selecting traits that confer resilience to climate-induced stressors (Bai & Plastow, 2022) ^[4]. Moreover, the application of a diverse genomic toolkit, including Genome-Wide Association Studies (GWAS), Quantitative Trait Loci (QTL) mapping, Whole-Genome Sequencing (WGS), and functional genomics, enables a detailed examination of the complex genetic architecture underlying thermotolerance, disease resistance, and metabolic efficiency (Hassanine et al., 2025) ^[22]. Consequently, climate resilience can now be investigated as a genetically regulated trait rather than a solely phenotypic response.

Furthermore, GWAS has been instrumental in identifying single nucleotide polymorphisms (SNPs) associated with adaptive phenotypes, particularly within indigenous pig populations (Mosquera-Rendón et al., 2023) ^[37]. In this regard, studies have identified key candidate genes, most notably members of the heat-shock protein (HSP) family and immune-regulatory gene clusters, which are critical for maintaining reproductive stability under environmental stress (Gilbert et al., 2025) ^[19]. However, the predictive accuracy of GWAS often declines under conditions of environmental heterogeneity. As a result, this limitation underscores the necessity of integrating Genotype-by-Environment (\$G \times \\$E\$) interactions into selection programmes to ensure that genetic gains remain stable across fluctuating climatic conditions (Bussiman et al., 2025) ^[10].

Additionally, WGS and QTL mapping provide the resolution required to detect rare and breed-specific alleles (Ben Zaabza et al., 2025) ^[7]. These climate-smart variants, which are frequently absent in cosmopolitan breeds, therefore constitute the genetic foundation for incorporating indigenous pigs into modern breeding strategies (Wang et al., 2025 ^[61]; Li et al., 2021) ^[29]. At the same time, the increasing emphasis on functional genomics, particularly through transcriptomic and epigenetic analyses, has clarified the molecular pathways underpinning metabolic plasticity and stress adaptation (Jianfang et al., 2025) ^[25]. Accordingly, by linking genotypes to specific biological outcomes, such as altered cytokine production or activation of stress-response pathways, functional genomics provides the mechanistic insight required for precision breeding (Joshi et al., 2024) ^[26].

Nevertheless, the application of genomic selection (GS), especially through reaction norm models, enables the prediction of breeding values across gradients of environmental severity (Dekkers, 2021 ^[14]; Fasil Getachew et al., 2024) ^[18]. Nevertheless, a persistent bottleneck remains in the form of the phenotyping gap. Specifically, the difficulty of obtaining accurate, high-throughput phenotypic data under variable environmental conditions, combined with small reference populations in indigenous breeds, continues to limit the widespread adoption of genomic selection models (Biscarini et al., 2021) ^[8].

In summary, the combined application of these genomic tools facilitates a transition from conventional selection practices towards a holistic, systems-biology approach. By integrating structural and functional genomic data, breeding programmes can effectively reconcile indigenous robustness with commercial productivity. Therefore, this integrated framework should be regarded not as an alternative strategy, but as a foundational requirement for securing sustainable pig production in an increasingly volatile global climate.

FUNCTIONAL INSIGHTS FROM INDIGENOUS AND COMMERCIAL BREEDS

Elucidating the functional mechanisms that underpin climate resilience is a fundamental prerequisite for the design of future-proof breeding programmes. In this context, adaptive capacity arises from the interaction between physiological homeostasis and molecular regulation. Accordingly, comparative analyses between indigenous and cosmopolitan breeds provide critical insights into the evolutionary trade-offs between productivity and environmental fitness (Pius et al., 2024) ^[44].

From a physiological standpoint, indigenous breeds demonstrate a clear adaptive advantage, primarily through enhanced thermoregulatory efficiency and metabolic flexibility (Gourdine et al., 2021) ^[20]. In contrast, highly selected commercial lines frequently experience metabolic overheating as a consequence of elevated basal growth rates (Nawaz et al., 2021) ^[39]. Indigenous populations, by comparison, generally maintain lower rectal temperatures and more stable respiration rates during periods of acute thermal exposure (Gourdine et al., 2021) ^[20]. Moreover, these breeds exhibit notable reproductive stability under low input management systems, reflecting an evolutionary strategy that prioritises biological robustness. Conversely, intensive selection for hyper-prolificacy and accelerated growth in commercial genotypes has inadvertently increased their sensitivity to thermal load (Majeed et al., 2021) ^[33]. Consequently, when ambient temperatures exceed the thermoneutral zone, these high output lines display pronounced declines in feed conversion efficiency and reproductive longevity (Brito et al., 2024) ^[9].

At the molecular level, further divergence in adaptive strategies becomes evident. Chauhan et al., (2021) ^[11] notes that indigenous pigs consistently exhibit a more responsive cellular defence system, as reflected by the rapid and sustained upregulation of heat shock proteins and the activation of antioxidant enzyme pathways. In addition, genomic analyses of these populations reveal rare alleles associated with pathogen recognition and innate immune competence. Notably, many of these alleles have been substantially reduced or lost in industrial germplasm as a result of narrowly defined selection objectives (Li et al., 2024) ^[30].

Nevertheless, the expression and effectiveness of these functional traits are strongly influenced by genotype-by-environment interactions (Napier et al., 2023) ^[38]. Accumulating, Raffo and Jensen, (2023) ^[46] indicates that alleles conferring resilience in extensive tropical production systems may not exhibit the same physiological utility within intensive temperate environments. Thus, this environmental dependency highlights the limitations of uniform breeding strategies and reinforces the importance of environment-specific selection approaches.

Collectively, the integration of physiological phenotyping with molecular marker information provides a comprehensive framework for sustainable genetic improvement (Upadhyay et al., 2024) ^[60]. By positioning indigenous breeds as functional reference populations, breeders can strategically introduce resilience-associated alleles into commercial lines while maintaining productivity (Tusingwiire, 2025) ^[59]. In this way, such an approach reconciles economic performance with biological endurance and offers a scientifically grounded pathway for strengthening global food security under increasing climatic pressure.

BREEDING STRATEGIES FOR SUSTAINABLE CLIMATE RESILIENCE

Breeding strategies for climate-resilient pig production increasingly require a shift away from conventional single-trait selection towards integrated and systems-based genetic frameworks. Historically, pig breeding programmes have prioritised growth rate and carcass yield in isolation. However, such approaches are no longer sufficient in the context of rising thermal stress, evolving disease pressures, and heterogeneous production environments (Michael et al., 2021 ^[36]; Snelling et al., 2022) ^[57]. Consequently, sustainable genetic improvement now depends on combining productivity goals with adaptive capacity through the coordinated use of functional traits, genomic technologies, and indigenous genetic resources (Dekkers, 2025) ^[15].

Central to this transition is the application of multi-trait selection indices, which enable the simultaneous improvement of productivity and resilience traits. By assigning appropriate biological and economic weights to characteristics such as thermotolerance, metabolic efficiency, disease resistance, and reproductive robustness, breeders can manage productivity and resilience trade-offs without undermining economic performance (Inouye et al., 2021 ^[24]; Cheruiyot et al., 2022) ^[13]. In addition, reaction norm models provide a robust analytical basis for capturing genotype and environment interactions. This allows selection for performance stability across diverse and changing climatic conditions rather than optimisation within a single production setting (Waters et al., 2023) ^[63].

Alongside this, advances in genomic selection and precision phenotyping have significantly improved the efficiency of resilience-focused breeding. High-density SNP panels and whole-genome sequencing support the identification and integration of climate-adaptive alleles into genomic estimated breeding values, thereby accelerating genetic progress for complex adaptive traits (Cheruiyot et al., 2022 ^[13]; Oke et al., 2025) ^[41]. Furthermore, sensor-based phenotyping and emerging digital twin technologies enhance selection accuracy by enabling predictive modelling of stress responses prior to environmental exposure. This strengthens breeding decisions under climatic uncertainty (Sinha et al., 2023 ^[55]; Sharma et al., 2025) ^[53].

Nevertheless, the effective implementation of climate-resilient breeding strategies remains context-specific. Smallholder systems generally prioritise low-input robustness and community-based improvement approaches, whereas industrial systems rely on capital-intensive genomic integration to maintain a balance between productivity and resilience at scale (Sinha et al., 2023 ^[55]; Bashiru and Oseni, 2025) ^[6]. Moreover, the conservation of indigenous germplasm through cryopreservation and structured introgression should be viewed not only as biodiversity preservation but also as a strategic safeguard for maintaining adaptive genetic variation essential for future breeding programmes (Engdawork et al., 2024) ^[17].

Overall, sustainable climate-resilient pig breeding requires a multi-layered framework that integrates functional traits, genomic precision, indigenous genetic resources, and adaptive modelling approaches. Such an integrated strategy aligns with climate-smart livestock principles and represents a viable pathway for safeguarding food security, animal welfare, and the long-term viability of pig production systems under increasing climatic pressure (Osbahe, 2007 ^[42]; Chen, 2025) ^[12].

Table 3: Breeding Framework for Climate Resilient Pigs

Framework component	Description	Tools and methods
Systems based breeding orientation	Shifts selection focus from isolated productivity traits to integrated resilience and performance under climate stress (Dekkers, 2025).	Integrated breeding objectives and systems-based selection design

Multi trait selection indices	Balance adaptive and productive traits to manage productivity and resilience trade-offs (Inouye et al., 2021; Cheruiyot et al., 2022).	Multi trait indices with biological and economic weighting
Reaction norm modelling	Supports selection for performance stability across variable climatic environments through genotype and environment analysis (Waters et al., 2023).	Reaction norm models and environmental sensitivity analysis
Genomic selection for adaptation	Improves selection accuracy for thermotolerance, immunity, and metabolic efficiency (Cheruiyot et al., 2022).	SNP panels, whole genome sequencing, genomic estimated breeding values
Precision phenotyping	Captures real time adaptive responses under stress conditions (Sinha et al., 2023).	Sensor based monitoring of body temperature, activity, and feed intake
Digital twin technologies	Enables predictive assessment of stress resilience prior to exposure (Sharma et al., 2025).	Digital twin modelling and sensor genomic integration
Indigenous genetic resource integration	Introduces locally adapted alleles while maintaining genetic diversity (Oke et al., 2025).	Structured introgression and adaptive crossbreeding
Germplasm conservation	Preserves adaptive genetic variation for long term resilience (Engdawork et al., 2024).	Cryopreservation and gene banks
Context specific implementation	Aligns breeding strategies with smallholder and industrial production systems (Sinha et al., 2023; Bashiru and Oseni, 2025).	Low input resilience breeding and genomic integration
Institutional and policy support	Facilitates the adoption and sustainability of climate resilient breeding strategies (Osbaahr, 2007).	Capacity building, infrastructure development, and international collaboration

FUTURE DIRECTIONS AND RESEARCH GAPS

Although substantial progress has been made in identifying the genetic and functional foundations of climate resilience in pigs, important research gaps continue to constrain the effective translation of scientific advances into operational breeding programmes (Pius et al., 2024) ^[44]. A central limitation remains the scarcity of high-quality, standardised phenotypic data for adaptive traits, particularly within indigenous and smallholder production systems. Traits such as thermotolerance, disease resistance, and metabolic efficiency are inherently complex and context-dependent, and current measurement protocols remain fragmented and inconsistent (Neethirajan and Kemp, 2021) ^[40]. Nevertheless, recent developments in sensor-based and wearable technologies present a promising pathway for generating continuous, real-time phenotypic data that can strengthen selection for resilience (Pyrkov et al., 2021) ^[45].

In parallel, the integration of multi-trait and multi-environment genomic models remains insufficiently developed. Although reaction norm and genotype-by-environment frameworks are essential for predicting performance under climatic variability, their application is limited by the availability of large, well-characterised datasets that span diverse environments (Halpin-McCormick et al., 2024) ^[21]. Expanding genomic reference populations to include indigenous and locally adapted breeds is therefore critical for capturing a broader spectrum of adaptive alleles and improving the robustness of genomic predictions (Roorkiwal et al., 2018) ^[47].

Moreover, functional genomics represents an important frontier for advancing climate-resilient breeding.

Transcriptomic, epigenetic, and proteomic approaches can deepen understanding of the biological pathways underpinning thermoregulation, immune competence, and metabolic resilience (Singh et al., 2022) ^[54]. In this context, gene-editing technologies such as CRISPR-Cas9 offer potential for targeted incorporation of adaptive

alleles, particularly from indigenous populations. However, their application must be carefully evaluated in light of ethical considerations, regulatory constraints, and public acceptance (Schwartz et al., 2025) ^[50].

At the same time, the conservation of indigenous genetic resources remains a strategic priority. Genetic erosion driven by indiscriminate crossbreeding and the expansion of intensive production systems threatens the long-term availability of climate-adaptive variation (Aguilar, 2021) ^[3]. Consequently, structured conservation initiatives, including cryopreservation and controlled introgression programmes, are essential to safeguard these resources for future breeding efforts (Tejasree, 2024) ^[58].

Finally, effective translation of research into practice depends on supportive policy frameworks, capacity building, and international collaboration. Breeding strategies must be aligned with the realities of both smallholder and industrial systems, particularly in regions most vulnerable to climate change (Barrett et al., 2011) ^[5]. Addressing these interconnected gaps will enable future research to accelerate the development of climate-resilient pig populations that balance productivity, adaptation, and sustainability, thereby contributing meaningfully to global food security objectives.

CONCLUSION

Climate change increasingly threatens global pig production by disrupting growth performance, reproductive efficiency, disease resistance, and overall system stability, with impacts most pronounced in tropical and subtropical regions. In this context, indigenous pig breeds emerge as a critical yet underutilised genetic reservoir, having evolved adaptive traits such as thermotolerance, disease resilience, and efficient feed utilisation under harsh environmental conditions. At the same time, advances in genomic technologies including genome wide association studies, whole genome sequencing, functional genomics, and genomic selection have created new opportunities to systematically identify, validate, and deploy these adaptive attributes within modern breeding programmes.

Consequently, the integration of functional traits, genomic information, and indigenous genetic resources within multi trait and environment responsive breeding frameworks represents a viable and sustainable strategy for sustaining productivity under climatic stress. Importantly, the conservation and structured use of local breeds is not merely a biodiversity objective but a prerequisite for long term breeding resilience. Looking ahead, research efforts should prioritise improved phenotyping accuracy, broader and more diverse reference populations, responsible application of gene editing tools, and stronger pathways linking scientific innovation to farm level implementation.

Overall, by aligning indigenous genetic potential with contemporary genomic approaches, pig breeding programmes can deliver animals that combine productivity with resilience, thereby supporting sustainable livestock systems and contributing to global food security in an increasingly warming world.

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