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Enhancing Climate Resilience in Tropical Dairy Production: The Potential of Quality Slick Genetics for Smallholder Dairy Systems in Indonesia

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A B S T R A C T

This study develops a quantitative simulation-based predictive model to assess the potential of slick hair genetics in maintaining milk production under increasing Temperature–Humidity Index (THI) conditions in lowland smallholder dairy systems in Java, Indonesia. Secondary climatic, genetic, physiological, and production parameters from studies published between 2020 and 2025 were integrated into four THI scenarios. Predicted milk yield declined in both genetic groups as THI increased, but the reduction was smaller in slick dairy cows than in non-slick dairy cows, at 8.04% and 10.11%, respectively. The slick genetics × THI interaction indicated a buffering effect on heat-related production losses. These findings support slick genetics as a potential climate-adaptation strategy, although longitudinal field validation using genotyped dairy cows remains necessary.

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INTRODUCTION

Climate change has become a major challenge to the sustainability of livestock production, particularly in tropical regions where dairy cows are continuously exposed to high ambient temperatures and relative humidity. These environmental conditions increase the risk of heat stress, which can reduce feed intake, milk production, reproductive efficiency, and animal welfare (Thornton et al., 2022; Polsky & von Keyserlingk, 2021). The thermal burden experienced by dairy cows is determined not only by air temperature but also by the interaction between temperature and humidity. The Temperature–Humidity Index (THI) is therefore widely used as a physical indicator of environmental heat load and the potential risk of heat stress in dairy production systems (West, 2021; Saputra et al., 2023). Without appropriate adaptation strategies, increasing climatic pressure is expected to intensify productivity losses and threaten the long-term sustainability of tropical dairy farming (Rojas-Downing et al., 2021; Carabaño et al., 2022).

In Indonesia, dairy production is dominated by smallholder farming systems that commonly maintain Holstein Friesian dairy cows and their crosses. These dairy cows have high milk-production potential but are relatively sensitive to elevated temperature and humidity because they originated from temperate environments (Hidayat et al., 2021; Asmarasari et al., 2023). The vulnerability may be greater in lowland and coastal areas of Java, including parts of West Java, Central Java, and East Java, where persistently warm and humid conditions can constrain heat dissipation and increase the frequency of high-THI exposure. This environmental challenge is particularly relevant because smallholder farmers often have limited access to mechanical ventilation, sprinkler systems, climate-controlled housing, and other capital-intensive cooling technologies (Hidayati et al., 2021; Sodiq et al., 2022). Consequently, adaptation strategies for lowland dairy systems must be biologically effective, economically feasible, and compatible with existing smallholder production conditions.

Genetic adaptation has increasingly been recognized as a promising long-term strategy for improving livestock resilience under climate-related stress. Unlike temporary management interventions, adaptive genetic traits are heritable and can provide continuous benefits across production cycles and generations (Sutrisno et al., 2022; Carabaño et al., 2022). One of the most relevant thermotolerance traits is the slick hair characteristic, which is associated with shorter and smoother hair coats that facilitate heat dissipation and reduce the accumulation of body heat under hot environmental conditions (Dikmen et al., 2021; Porto-Neto et al., 2021). Dairy cows carrying slick-associated genetic traits have been reported to maintain more favorable body temperatures, respiration rates, and physiological stability than non-slick dairy cows during periods of thermal stress (Boonkum et al., 2021; Nguyen et al., 2022). These biological advantages may allow a greater proportion of metabolic energy to be allocated to milk production rather than to maintaining thermal equilibrium.

However, slick genetics does not eliminate environmental heat load. Instead, it may alter the magnitude of the biological and productive responses of dairy cows to increasing THI. Under relatively moderate thermal conditions, differences in milk-production performance between slick and non-slick dairy cows may be limited because both groups remain within manageable physiological conditions. At higher THI levels, however, dairy cows with thermotolerant slick characteristics are expected to dissipate heat more effectively and experience a smaller decline in milk production. This suggests that the productive contribution of slick genetics is conditional on the level of environmental heat exposure, making THI theoretically relevant as a physical moderating variable rather than merely as a direct predictor of production performance (Herbut et al., 2022; Li et al., 2021).

Despite growing scientific interest in genetic thermotolerance, most research on slick genetics has been conducted in experimental settings or large-scale commercial production systems outside Indonesia. Evidence regarding its potential application in tropical smallholder farms, particularly in lowland areas of Java, remains limited (Garcia et al., 2022; Nguyen & Tran, 2023). Indonesian dairy adaptation studies have also concentrated primarily on feed management, housing improvement, water provision, and other environmental interventions, while genetic-based adaptation has received comparatively less attention (Wahyudi et al., 2022; Prasetyo et al., 2022). Moreover, previous studies commonly examine genetic traits, physiological heat responses, THI, and milk production separately, resulting in an incomplete understanding of how these factors interact within a unified predictive framework.

An additional research gap concerns the analytical position of THI. Previous livestock studies have generally treated THI as a direct environmental determinant of heat stress or milk-production decline (Wicaksono et al., 2021; Prabowo et al., 2024). Limited attention has been given to whether THI changes the strength of the relationship between adaptive genetics and production performance. Consequently, it remains unclear whether the predicted productive advantage of slick dairy cows becomes increasingly pronounced as environmental heat load rises. Addressing this gap requires a quantitative predictive model that includes measurable variables, direct effects, and an interaction term between slick genetic status and THI. A simulation-based approach is particularly relevant where local longitudinal data on genotyped slick and non-slick dairy cows remain limited but sufficient climatic and biological parameters are available from previous empirical studies (Kurniawan et al., 2022; Rahman et al., 2023).

Therefore, this study develops a quantitative simulation-based predictive framework to estimate the potential contribution of slick hair genetics to milk-production stability in lowland smallholder dairy systems in Java, Indonesia. Slick genetic status is positioned as the principal predictor, milk production as the outcome variable, and THI as a physical moderating variable. The model examines the direct effect of slick genetics on milk-production performance, the negative effect of increasing THI, and the interaction between slick genetics and THI. The framework integrates secondary climatic parameters, genetic-response coefficients, physiological indicators, and milk-production relationships derived from previous empirical research.

The study provides both theoretical and practical contributions. Theoretically, it extends climate-resilience research by conceptualizing THI as an environmental condition that may strengthen or weaken the productive benefit of adaptive genetics. It also provides a quantitatively testable structure that connects genetic type, environmental heat load, and milk-production stability. Practically, the framework offers preliminary evidence for evaluating slick genetics as a potentially sustainable and cost-effective component of breeding strategies for lowland dairy systems in Java. Nevertheless, the proposed relationships require subsequent validation using genotyped dairy cows, repeated THI observations, physiological measurements, and daily milk-production records before they can be applied to operational breeding and farm-management decisions.

LITERATURE REVIEW

Predictive Modeling in Livestock Systems

Predictive modeling provides a quantitative approach for estimating livestock performance based on genetic, environmental, physiological, and management variables. In dairy production, climatic information can be integrated with milk-yield records to identify heat-stress thresholds and estimate production changes under different environmental conditions. Random-regression and nonlinear models are particularly relevant because individual dairy cows may exhibit different production responses as thermal pressure increases (Mbuthia et al., 2021). Predictive models can also incorporate repeated THI observations to represent variations in environmental exposure and milk-production performance more accurately. In this study, predictive modeling is applied through a quantitative simulation-based framework. Parameters obtained from previous empirical studies are used to specify the relationships among slick genetic status, THI, and milk-production stability. This approach enables the direct effects of genetic and environmental variables, as well as their interaction, to be examined within an integrated analytical framework.

Genetic Adaptation and Thermotolerance

Genetic thermotolerance refers to the inherited ability of dairy cows to maintain physiological stability and production performance under increasing environmental heat load. Heat-tolerant dairy cows generally experience smaller increases in body temperature and less severe milk-production decline than heat-sensitive dairy cows. This variation indicates that adaptation to heat stress is influenced not only by farm management but also by differences in genetic capacity. Genomic studies have demonstrated that dairy cows differ in their sensitivity to increasing THI and that heat-tolerance traits can be estimated independently from general milk-production potential. McWhorter et al. (2023) found genetic variation in production responses to heat stress among Holstein and Jersey dairy cows. Similarly, Oloo et al. (2024) showed that heat resilience can be evaluated through differences in physiological and production responses across environmental conditions. Genetic adaptation therefore provides an important foundation for developing dairy cows that are more suitable for lowland tropical systems.

Slick Hair Genetics as a Predictive Variable

Slick hair genetics is associated with mutations in the prolactin receptor gene, particularly the SLICK1 allele. Dairy cows carrying this trait generally have shorter and smoother hair, which facilitates heat dissipation and supports body-temperature regulation during thermal exposure. Slick genetic status should therefore be determined through genetic testing or reliable pedigree information rather than solely through visual observation of hair characteristics (Sosa et al., 2022). Research on slick-haired Holstein dairy cows under tropical conditions has reported lower body temperatures and more favorable mammary blood flow than in wild-type Holsteins. These physiological advantages indicate that slick dairy cows may allocate less energy to thermoregulation and maintain biological processes associated with milk synthesis more effectively (Contreras-Correa et al., 2024). Differences in milk-production performance have also been observed among dairy cows carrying different numbers of SLICK1 alleles, although further comparisons with non-slick dairy cows remain necessary (Donkersloot et al., 2025). Within the proposed model, slick genetic status is treated as the principal predictor of milk-production stability. Slick dairy cows are expected to experience a smaller decline in production when exposed to increasing temperature and humidity than non-slick dairy cows.

H1: Slick hair genetics positively predicts milk-production stability in lowland dairy systems.

Heat Stress, THI, and Dairy Productivity

Heat stress occurs when the environmental heat load exceeds the animal's capacity to dissipate accumulated body heat. The Temperature–Humidity Index combines ambient temperature and relative humidity to represent the thermal conditions experienced by dairy cows. In smallholder systems, increasing THI has been associated with reductions in feed intake, physiological stability, and daily milk production (Ekine-Dzivenu et al., 2020). The effect of THI on milk production may vary across different levels of thermal exposure. Under moderate conditions, dairy cows may maintain production through physiological adaptation, whereas prolonged or elevated THI can increase the energy required for thermoregulation. Consequently, energy that would otherwise support milk synthesis is redirected toward maintaining body temperature. THI has therefore been incorporated into dairy-production models to estimate changes in milk yield and lactation performance under heat-stress conditions (M'Hamdi et al., 2021). In this study, THI is treated as a direct environmental predictor of milk-production performance in lowland dairy systems.

H2: An increase in the Temperature–Humidity Index negatively predicts milk production in lowland dairy systems.

Temperature–Humidity Index as a Moderating Variable

A moderating variable determines whether the strength of a relationship changes under different conditions. THI is positioned as a physical moderator because the productive advantage of slick genetics is expected to depend on the level of environmental heat load. The contribution of slick genetics may be limited under relatively comfortable conditions but become more evident when temperature and humidity increase. At lower THI levels, slick and non-slick dairy cows may maintain relatively similar production because both groups remain capable of regulating body temperature. At higher THI levels, non-slick dairy cows are expected to experience a greater decline in milk yield, whereas slick dairy cows are predicted to maintain a more stable production response. Reaction-norm analysis supports this assumption by showing that genetic expression and milk-production responses can vary across the THI scale (Oloo et al., 2024).

The moderating role of THI is therefore reflected in the interaction between slick genetic status and environmental heat load. The advantage of slick genetics is expected to increase as thermal pressure becomes more severe.

H3: The Temperature–Humidity Index moderates the relationship between slick hair genetics and milk-production stability.

H4: The negative effect of increasing THI on milk production is weaker in slick dairy cows than in non-slick dairy cows.

Smallholder Dairy Systems and Adaptation Constraints

Smallholder dairy farmers often face financial and infrastructural limitations that restrict their ability to adopt mechanical ventilation, sprinklers, and climate-controlled housing. Although these technologies can reduce heat stress, their installation and maintenance may create additional financial burdens for farms with limited capital (Ogundeji et al., 2021). The capacity to implement climate-adaptation measures is also influenced by access to financial, physical, human, and institutional resources (Wahyono et al., 2023).

These constraints are particularly relevant to lowland and coastal dairy-production environments in West Java, Central Java, and East Java, where high temperature and humidity may increase dairy cow exposure to thermal stress. Slick genetics may provide a long-term adaptation option because thermotolerance is embedded in the animal and can be transferred through breeding. Nevertheless, genetic adaptation should complement adequate water provision, shade, ventilation, feed management, housing, and animal-health practices rather than replace them.

METHODOLOGY

Research Design and Approach

This study employed a quantitative simulation-based predictive design to estimate the potential effect of slick hair genetics on milk-production stability under varying Temperature–Humidity Index (THI) conditions. Slick genetic status was treated as the main predictor, milk production as the outcome variable, and THI as both a direct environmental predictor and a moderating variable. The study did not collect primary field data. Instead, the model integrated secondary climatic parameters, genetic-response coefficients, physiological evidence, and milk-production relationships reported in previous empirical studies. The biological simulation was further extended to estimate potential herd-level economic and operational implications using a representative smallholder baseline of 10 lactating cows. This design allowed the direct and interactive effects of slick genetics and THI to be examined quantitatively and translated into preliminary indicators of milk-output efficiency, feed-cost efficiency, cooling-related investment requirements, and emission intensity, without presenting the results as direct observations from Indonesian dairy farms (Salamone et al., 2022).

Study Setting and Lowland Context

The predictive setting represented smallholder dairy systems in lowland and coastal environments of West Java, Central Java, and East Java. Lowland environments were defined as production areas located approximately below 300 meters above sea level. These areas were selected because their relatively high temperature and humidity create relevant conditions for evaluating genetic thermotolerance. The regions were treated as simulation contexts rather than field-research locations. The model therefore represented possible climatic conditions in lowland Java without assuming that all locations had identical environmental and production characteristics.

Data Sources and Parameter Selection

The study used secondary quantitative parameters obtained from peer-reviewed articles, scientific reports, climatic records, and dairy-production studies published between 2020 and 2025. Sources were selected when they reported measurable information on slick genetics, the SLICK1 allele, temperature, relative humidity, THI, physiological responses, or milk production. Priority was given to studies comparing slick and non-slick dairy cows, examining different SLICK1 genotypes, or estimating milk-production responses under increasing heat exposure. For the economic extension, relevant secondary parameters related to feed expenditure, milk-output valuation, cooling equipment and electricity requirements, and greenhouse-gas emission intensity were used where comparable information was available. Studies without clear measurement procedures or quantitative parameters were excluded. The selection and documentation process followed structured review principles to improve transparency and reproducibility (Page et al., 2021).

Data Collection and Parameter Extraction

A literature-extraction matrix was used to record study location, dairy cow breed, slick genetic status, temperature, relative humidity, THI, physiological indicators, daily milk production, and the magnitude of the reported response to heat exposure. Climatic parameters were obtained from studies reporting temperature and humidity measurements. Genetic parameters were derived from studies involving genetically verified slick, non-slick, or wild-type dairy cows. Production parameters were obtained from studies reporting daily milk yield or production decline under increasing THI conditions. Economic and operational parameters were additionally extracted where available to support scenario-based estimates of herd-level milk output, feed-cost efficiency, cooling-related costs, and greenhouse-gas emission intensity. Cross-study comparison was used to determine plausible parameter ranges and reduce reliance on a single source.

Measurement of the Temperature–Humidity Index

THI was calculated from ambient temperature and relative humidity using a standard THI formulation for dairy cows. It was analyzed as a continuous variable to represent gradual changes in environmental heat load. For descriptive interpretation, THI was also divided into four simulation scenarios.

Table 1. THI Scenarios Used in the Predictive Simulation

Scenario	Temperature (°C)	Relative Humidity (%)	THI	Heat-Load Category
Scenario 1	23	75	71.28	Comfortable
Scenario 2	26	70	75.37	Mild heat stress
Scenario 3	30	75	82.15	Moderate heat stress
Scenario 4	34	85	90.30	Severe heat stress

Scenario 1 represented the reference condition, while the remaining scenarios represented progressively higher environmental heat loads.

Operationalization of Variables

Slick hair genetics was treated as the independent variable. Slick status was determined from genetic verification or reliable pedigree information rather than visual hair characteristics alone. THI was treated as a direct predictor and moderating variable, while predicted daily milk production was the main dependent variable. Milk-production stability referred to the ability of dairy cows to maintain production as THI increased. Parity, days in milk, feed quality, water availability, housing, ventilation, cooling access, and farm location were treated as control variables. For the economic extension, herd-level milk production was estimated for 10 lactating cows, while feed-cost efficiency, cooling-related operating and investment requirements, and emission intensity were treated as supplementary management and business indicators rather than additional causal variables in the biological model.

Table 2. Operationalization of Research Variables

Variable	Analytical Role	Operational Measurement
Slick hair genetics	Independent variable	1 = genetically verified slick dairy cow; 0 = non-slick dairy cow
THI	Predictor and moderator	Continuous index derived from temperature and humidity
Milk production	Dependent variable	Predicted milk yield per cow per day

Milk-production stability	Outcome indicator	Absolute or percentage production decline across THI levels
Slick × THI	Interaction effect	Difference in THI response between slick and non-slick dairy cows
Rectal temperature	Supporting indicator	Degrees Celsius
Respiration rate	Supporting indicator	Breaths per minute
Parity and days in milk	Control variables	Reproductive history and lactation stage
Feed, water, and housing	Control variables	Standardized management conditions
Farm location	Control variable	Elevation, province, and coastal characteristics

The control variables were held at comparable reference conditions in the main simulation to isolate the predicted effects of slick genetics and THI. Economic indicators were calculated subsequently from the predicted production differences and therefore did not alter the coefficients of the primary slick genetics–THI model.

Simulation Procedure

The simulation began by establishing baseline milk production for non-slick dairy cows under the lowest THI scenario. The slick dairy-cow baseline was calibrated using proportional production differences reported in eligible tropical studies. THI was then increased progressively across the four scenarios. Milk-production responses were estimated using THI-related decline parameters and genetic-response coefficients obtained from the selected literature. Slick and non-slick dairy cows were compared at each THI level. Moderation was indicated when slick dairy cows experienced a smaller production decline than non-slick dairy cows as THI increased. All numerical outputs were treated as literature-calibrated predictions rather than

To evaluate potential economic implications, the predicted per-cow milk yields were subsequently scaled to a representative smallholder herd of 10 lactating cows. Herd-level output was calculated by multiplying predicted daily milk production per cow by 10. The resulting production estimates were used to examine potential differences in milk-output value and feed cost per unit of milk. Cooling adaptation was evaluated comparatively through scenario-based requirements for equipment such as fans or blowers, including associated investment, electricity, and operating implications. Carbon performance was expressed as greenhouse-gas emission intensity relative to milk output, allowing the model to assess whether more stable production could reduce emissions per unit of milk produced. These economic and carbon estimates were treated strictly as literature-calibrated scenarios and not as observed financial or emission records from individual farms.

Data Analysis Techniques

The analysis examined the direct effect of THI by comparing milk production across increasing heat-load scenarios. The direct contribution of slick genetics was assessed by comparing slick and non-slick dairy cows under equivalent environmental conditions. The moderating role of THI was examined through differences in the production-response patterns of the two genetic groups. A positive interaction pattern indicated that slick genetics buffered part of the negative effect of increasing THI. Results were presented as predicted daily milk production, absolute differences, percentage changes from baseline, model coefficients, and an interaction graph.

The economic extension compared slick and non-slick scenarios at the 10-cow herd level using predicted total milk output, potential milk-output value, feed cost per unit of milk, and cooling-related investment and operating implications. Carbon efficiency was evaluated using emission intensity, expressed as greenhouse-gas emissions relative to the quantity of milk produced. The economic analysis was descriptive and scenario-based; therefore, it was used to assess potential managerial and operational implications rather than to infer statistically significant financial effects.

Table 3. Criteria for Interpreting the Predictive Model

Model Component	Expected Direction	Interpretation
Slick genetic effect	Positive	Slick dairy cows maintain more stable production
THI effect	Negative	Increasing THI reduces milk production
Slick × THI interaction	Positive	Slick genetics weakens the negative THI effect
Non-slick response	Steeper decline	Greater sensitivity to thermal pressure
Slick response	Flatter decline	Greater milk-production stability

Because the coefficients were derived from secondary literature, standard errors, t-values, and p-values were not artificially generated. Statistical significance was reported only when available from the original calibration studies. The same principle was applied to the economic extension: no farm-level profit, cost-saving, or carbon-reduction effect was presented as statistically confirmed unless supported by empirical source data.

Sensitivity Analysis and Model Validation

Sensitivity analysis was conducted by varying the baseline production level, THI-related production decline, and buffering contribution of slick genetics. The model was considered directionally stable when increasing THI consistently reduced milk production and slick dairy cows consistently showed a smaller decline. Model validity was evaluated through cross-study consistency, biological plausibility, and sensitivity analysis. For the economic extension, sensitivity interpretation also considered changes in relevant cost and operational assumptions, particularly feed expenditure, milk value, and cooling requirements, to avoid dependence on a single economic scenario. Conventional accuracy indicators such as RMSE, MAE, and cross-validation could not be calculated because an independent observed dataset of genotyped slick and non-slick dairy cows from Java was unavailable. The results were therefore interpreted as quantitative predictions. External validation will require longitudinal observations involving genetically verified dairy cows, repeated THI measurements, physiological indicators, daily milk-production records, and comparable farm-management information, together with actual farm-level feed costs, cooling-energy consumption, investment expenditure, milk prices, and greenhouse-gas emission records to validate the economic predictions.

RESULT AND DISCUSSION

THI Scenario Description

Four thermal scenarios were developed to represent increasing heat exposure in lowland dairy environments. The selected temperature and relative-humidity values were within the range reported for Indonesian tropical and lowland dairy environments. A lowland study conducted at an elevation of 187 m above sea level recorded barn temperatures of 23–30°C and relative humidity of 63–86%, while broader Indonesian conditions may reach approximately 34°C with high relative humidity (Adhyatma et al., 2024; Asmarasari et al., 2023).

The calculated THI values ranged from 71.28 under the comfortable scenario to 90.30 under severe thermal exposure. The first scenario represented conditions near the upper limit of thermal comfort. The mild and moderate scenarios represented increasingly stressful conditions, while the severe scenario reflected the combination of high temperature and humidity that may occur during extreme daytime conditions.

Table 4. Simulated Temperature–Humidity Index Scenarios for Lowland Dairy Systems

Scenario	Temperature (°C)	Relative Humidity (%)	Calculated THI	Heat-Load Category
Scenario 1	23	75	71.28	Comfortable
Scenario 2	26	70	75.37	Mild heat stress
Scenario 3	30	75	82.15	Moderate heat stress
Scenario 4	34	85	90.30	Severe heat stress

The classifications were interpreted according to the ranges applied in lowland dairy research, where THI values below approximately 72 indicate comparatively comfortable conditions, values of 72–80 indicate mild stress, values of 80–89 indicate moderate stress, and values beginning around 90 indicate severe heat stress.

Direct Effect of THI on Predicted Milk Production

The reference milk-production value for non-slick dairy cows was established at 7.07 L/cow/day. This value was calculated from the mean daily production of four FH crossbred cows reported in a lowland Indonesian study, namely 9.55, 7.80, 6.19, and 4.75 L/cow/day. The resulting reference value was used only to calibrate the simulation and did not represent the average production of all dairy cows in Java.

The THI response parameter was derived from the same study, which reported a decline of 0.030 L in morning milk production and 0.0076 L in afternoon milk production for each one-unit increase in THI. Because daily production consisted of both milking periods, the simulation applied a combined decline of 0.0376 L/cow/day per THI unit. The source estimates were negative but individually nonsignificant, with relatively low coefficients of determination. They were therefore used as local calibration parameters rather than definitive causal estimates.

Predicted non-slick milk production declined from 7.07 L/cow/day at THI 71.28 to 6.36 L/cow/day at THI 90.30. This represented a simulated reduction of approximately 10.11% from the comfortable to severe scenario. The pattern supports the expected negative relationship between environmental heat load and milk-production performance.

Direct Effect of Slick Hair Genetics

The direct slick-genetic parameter was calibrated using a tropical comparison in which slick Holsteins produced an average of 16.59 kg/day and wild-type Holsteins produced 14.83 kg/day. This descriptive difference was equivalent to approximately 11.9%. However, the original comparison was not statistically significant. Accordingly, the value was used only as a simulation parameter and must not be interpreted as confirmed evidence that slick dairy cows in Java will produce 11.9% more milk (Ortiz-Uriarte et al., 2020).

Applying this proportional difference to the local reference production generated a slick dairy-cow baseline of approximately 7.91 L/cow/day. Under increasing THI, slick dairy cows were also predicted to experience production losses, but the decline was smaller than that of non-slick dairy cows.

Table 5. Non-Slick Dairy Cows Across THI Scenarios

Scenario	THI	Non-Slick Production (L/cow/day)	Slick Production (L/cow/day)	Predicted Difference (L/cow/day)	Non-Slick Change from Baseline (%)	Slick Change from Baseline (%)
Comfortable	71.28	7.07	7.91	0.84	0.00	0.00
Mild heat stress	75.37	6.92	7.78	0.86	−2.17	−1.73
Moderate heat stress	82.15	6.66	7.55	0.88	−5.78	−4.60
Severe heat stress	90.30	6.36	7.28	0.92	−10.11	−8.04

The simulated results show that both genetic groups experienced declining milk production as THI increased. Nevertheless, slick dairy cows maintained higher predicted production and experienced a smaller proportional loss. The predicted production gap increased from 0.84 L/cow/day under comfortable conditions to 0.92 L/cow/day under severe heat exposure.

These results provide provisional model-based support for H1, which proposed that slick hair genetics positively predicts milk-production stability. However, H1 cannot be regarded as statistically confirmed because the direct slick parameter was transferred from an external tropical study and was not estimated using Indonesian field data.

Herd-Level Economic and Operational Prediction

To translate the biological prediction into a management context relevant to smallholder dairy farming, the per-cow estimates were scaled to a representative baseline herd of 10 lactating cows. This scaling does not introduce new empirical observations; it only converts the existing literature-calibrated milk-yield predictions into herd-level production indicators. A 30-day period was used for the monthly illustration.

Table 6. Predicted Herd-Level Milk Output for 10 Lactating Cows

Scenario	Non-Slick Milk (L/10 cows/day)	Slick Milk (L/10 cows/day)	Additional Slick Output (L/day)	Additional Slick Output (L/30 days)
Comfortable	70.7	79.1	8.4	252
Mild heat stress	69.2	77.8	8.6	258
Moderate heat stress	66.6	75.5	8.9	267
Severe heat stress	63.6	72.8	9.2	276

At severe heat exposure, the model predicts 63.6 L/day for a 10-cow non-slick herd and 72.8 L/day for an equivalent slick herd. The resulting difference of 9.2 L/day corresponds to approximately 276 L of additional milk over a 30-day period. The relative production advantage therefore becomes more economically relevant as THI increases, although it remains a simulated production difference rather than observed farm revenue. The potential gross economic value of this production difference can be expressed as:

$$\text{Additional milk value} = \Delta Q \times Pm$$

where ΔQ represents the predicted additional milk output and Pm represents the applicable farm-gate milk price. Under the severe scenario, the monthly production-value advantage is therefore equivalent to $276 \times Pm$. This formulation allows the model to be adapted to actual local milk prices without introducing an unsupported fixed price into the present simulation. Feed-cost efficiency can similarly be expressed as total feed expenditure divided by total milk output:

$$\text{Feed-cost efficiency} = Cf / Q$$

where Cf is total herd feed cost and Q is total milk production. If comparable feeding expenditure is assumed between the two genetic scenarios, the higher predicted milk output of slick dairy cows would reduce feed cost per liter of milk. Under the severe scenario, and only under the simplifying assumption of equal total feed expenditure, the modeled unit feed-cost index for the slick herd would be approximately 12.6% lower than for the non-slick herd because 72.8 L/day is produced instead of 63.6 L/day. This represents an efficiency scenario rather than evidence that slick dairy cows consume identical quantities or costs of feed in field conditions.

Cooling infrastructure was evaluated as an alternative adaptation cost rather than as a fixed observed expense. For conventional non-slick herds, maintaining milk production under high THI may require additional investment in fans, blowers, ventilation, sprinklers, electricity, and maintenance. The economic burden of cooling can therefore be represented as:

$$\text{Cooling cost per liter} = (\text{annualized cooling investment} + \text{electricity} + \text{maintenance}) / \text{milk output}.$$

At severe THI, the modeled additional output of 276 L/month from the slick scenario provides a practical break-even reference for comparing genetic adaptation with mechanical cooling. The monetary value of 276 × Pm represents the maximum monthly production value associated with the modeled slick advantage before considering the acquisition cost of slick genetics, feeding differences, or other management expenses. Actual comparisons between slick-genetic adoption and fan/blower investment require local equipment prices, power consumption, maintenance costs, and genetic-acquisition costs. Carbon performance was evaluated using emission intensity rather than absolute emission reduction:

$$\text{Emission intensity} = \text{Total GHG emissions } (tCO_2e) / \text{Milk output (t milk)}.$$

The economic carbon intensity may subsequently be expressed as emission intensity multiplied by the applicable carbon value per tCO_2e. Under an illustrative equal-total-emissions assumption, greater milk output would distribute the same emissions across a larger quantity of milk. At severe THI, the 72.8 L/day slick scenario would therefore have an emission-intensity index approximately 12.6% lower than the 63.6 L/day non-slick scenario. This value should not be interpreted as an observed reduction in biological methane or total farm emissions, because feed intake, manure emissions, electricity consumption, and cooling requirements were not directly measured in the present study.

Overall, the 10-cow simulation indicates that the potential value of slick genetics extends beyond biological heat tolerance to a management decision involving milk-output stability, unit feed cost, cooling investment, and carbon efficiency. However, these indicators remain conditional scenario estimates and require validation with actual farm-level prices, feeding costs, equipment costs, energy consumption, and greenhouse-gas inventories.

Moderating Effect of THI

The moderating effect was represented by the interaction between slick genetic status and THI. A recent large-scale genetic analysis found that improvement by one genetic standard deviation in heat tolerance could offset approximately 11% of milk-yield losses associated with heat stress. The simulation used this percentage as a conservative buffering parameter rather than treating it as a direct empirical SLICK1 estimate (Pook et al., 2025).

The non-slick THI coefficient was −0.0376 L/cow/day per THI unit. Applying an 11% buffering effect generated a slick–THI interaction coefficient of +0.0041 L/cow/day per THI unit. Consequently, the predicted THI slope for slick dairy cows was −0.0335 L/cow/day, compared with −0.0376 L/cow/day for non-slick dairy cows.

Table 7. Literature-Calibrated Predictive Model Coefficients

Predictor	Simulation Coefficient	Standard Error	t/z Value	p-Value	Interpretation
Reference production	7.07 L/cow/day	N/A	N/A	N/A	Predicted non-slick production at THI 71.28
Slick genetic status	+0.84 L/cow/day	N/A	N/A	N/A	Descriptive baseline advantage used for simulation
THI	−0.0376 L/cow/day per THI unit	N/A	N/A	N/A	Increasing THI reduces predicted milk production
Slick genetics × THI	+0.0041 L/cow/day per THI unit	N/A	N/A	N/A	Slick genetics buffers part of the negative THI effect
Parity, days in milk, feed, water, housing, and cooling	Held constant	N/A	N/A	N/A	Controlled conceptually to isolate the simulated genetic and THI effects

Note: Standard errors, test statistics, and p-values are not reported because these coefficients were literature-calibrated simulation inputs rather than estimates obtained from an individual-level empirical dataset.

The positive interaction coefficient indicates that slick genetics reduces part of the production decline associated with increasing THI. The interaction does not mean that slick dairy cows are unaffected by severe heat stress. Instead, it indicates that their predicted production slope is less negative than that of non-slick dairy cows. This pattern provides model-based support for H3 and H4. THI changes the predicted strength of the relationship between genetic status and production stability, while the negative effect of increasing THI is weaker among slick dairy cows. These findings remain predictive and require statistical confirmation using longitudinal field data.

Interaction Pattern Between Slick Genetics and THI

The interaction graph shows declining milk production in both genetic groups as THI increases. The non-slick line declines more steeply, whereas the slick line remains comparatively stable. The distance between the two lines increases slightly under moderate and severe heat exposure, indicating that the modeled benefit of slick genetics becomes more apparent as environmental heat load intensifies.

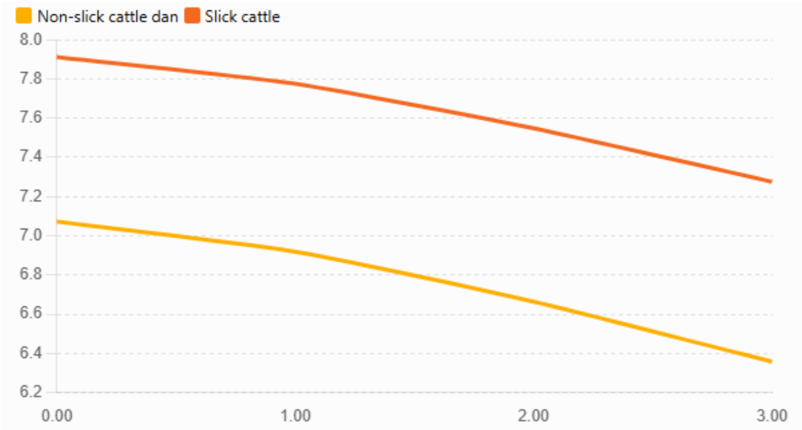

Figure 2. Interaction of Slick Hair Genetics and THI on Predicted Milk Production

At THI 71.28, the predicted difference between groups was 0.84 L/cow/day. At THI 90.30, the difference increased to 0.92 L/cow/day. This pattern indicates a buffering interaction rather than complete resistance to heat stress.

Effect of Control Conditions

The principal simulation held parity, days in milk, feed quality, water availability, housing, ventilation, and access to cooling at comparable reference levels. This decision was necessary to isolate the predicted effects of slick genetics and THI. Therefore, the main model did not estimate independent coefficients for each control variable.

The control variables nevertheless remain important when the model is applied to field data. The local calibration study showed that differences in lactation stage, health history, feed management, and milking conditions contributed to variation in milk production. Its THI models explained only 12.4% of morning production variation and 7.7% of afternoon production variation, indicating that most variation was associated with factors beyond THI alone.

The simulated genetic advantage should consequently be interpreted as conditional on comparable management conditions. Poor feed quality, restricted drinking water, inadequate ventilation, mastitis, and advanced lactation stage may reduce milk production independently of slick status.

Model Calibration and Accuracy Assessment

The simulation was calibrated using measurable environmental and milk-production parameters, but it could not yet be externally validated against an independent dataset of slick and non-slick dairy cows from Java. Therefore, conventional predictive-accuracy indicators such as RMSE and MAE could not be validly calculated.

Table 8. Model Calibration and Validation Status

Evaluation Indicator	Result	Interpretation
Morning THI calibration (R^2)	0.124	THI explained 12.4% of morning milk-production variation in the local source study
Afternoon THI calibration (R^2)	0.077	THI explained 7.7% of afternoon milk-production variation in the local source study
Morning THI source-model p-value	0.058	Negative relationship was not statistically significant at the 5% level
Afternoon THI source-model p-value	0.138	Negative relationship was not statistically significant at the 5% level
Directional consistency	Stable across four scenarios	Higher THI consistently reduced production
Interaction consistency	Stable across four scenarios	Slick dairy cows consistently showed a smaller proportional decline
RMSE	Not available	Requires observed validation data
MAE	Not available	Requires observed validation data
External validation	Not yet conducted	Requires genotyped dairy cows and repeated field measurements

The relatively low calibration (R^2) values confirm that THI alone is insufficient to explain milk-production variation. The proposed framework improves the conceptual specification by including genetic status and the slick–THI interaction, but its predictive accuracy cannot be claimed before external validation.

Likewise, the economic predictions should be interpreted as decision-support scenarios rather than validated profitability estimates. External economic validation requires actual farm-level milk prices, feed consumption and expenditure, genetic-acquisition costs, fan/blower investment and depreciation, electricity consumption, maintenance expenditure, and measured greenhouse-gas emissions.

Regional Prediction for Lowland Java

The four scenarios represent the thermal gradient that may occur across lowland and coastal dairy-production environments in West Java, Central Java, and East Java. However, the current model does not provide separate numerical estimates for each province because comparable regional datasets containing THI, genotyped slick status, milk production, and management variables were not available.

The scenario results may therefore be interpreted as general lowland-Java predictions rather than province-specific estimates. The comfortable and mild scenarios may reflect cooler morning or seasonally moderate conditions, whereas the moderate and severe scenarios represent hotter daytime or extreme humid conditions. Separate provincial comparisons should only be conducted after equivalent climatic and production data have been obtained for each region.

Summary of Hypothesis Evaluation

Table 9. Predictive Evaluation of the Research Hypotheses

Hypothesis	Simulation Result	Decision
H1: Slick hair genetics positively predicts milk-production stability	Slick dairy cows maintained higher simulated production across all THI scenarios	Provisionally supported
H2: Increasing THI negatively predicts milk production	Production declined continuously as THI increased	Supported by the simulation
H3: THI moderates the relationship between slick genetics and production stability	The difference between slick and non-slick production changed across THI levels	Provisionally supported
H4: The negative THI effect is weaker in slick dairy cows	Slick dairy cows experienced an 8.04% decline, compared with 10.11% in non-slick dairy cows under severe exposure	Provisionally supported

Overall, the simulation predicts that increasing THI reduces milk production in both genetic groups. Slick genetics does not eliminate thermal losses, but it produces a flatter decline and greater predicted production stability. Because the model uses secondary parameters, these findings should be described as provisional quantitative predictions, not as statistically confirmed evidence from Indonesian dairy farms. At the representative scale of 10 lactating cows, the same model predicts an additional slick-herd output of 8.4–9.2 L/day across the four THI scenarios, reaching approximately 276 L per 30 days under severe heat exposure. This herd-level advantage provides a quantitative basis for evaluating potential feed-cost efficiency, cooling-investment trade-offs, and carbon-emission intensity, while actual economic benefits remain subject to validation using observed farm-level cost, energy, emission, and market data.

The simulation indicates that increasing THI consistently reduces milk production in both slick and non-slick dairy cows, with non-slick dairy cows showing a predicted decline from 7.07 to 6.36 L/cow/day (10.11%) as THI increased from 71.28 to 90.30. This decline reflects the redistribution of metabolic energy from milk synthesis toward thermoregulation and is further influenced by reduced feed intake and physiological stress (Becker et al., 2020). Previous meta-analyses similarly reported that increasing heat stress decreases dry matter intake, milk yield, and feed efficiency (Chen et al., 2024). Unlike previous empirical studies, the present research translates these biological responses into a predictive framework specifically designed for lowland smallholder dairy systems in Java.

Slick dairy cows consistently maintained higher predicted milk production than non-slick dairy cows across all THI scenarios, although production declined in both groups as thermal stress increased. The simulated reduction was 8.04% for slick dairy cows compared with 10.11% for non-slick dairy cows, indicating that slick genetics provides partial thermotolerance rather than complete protection. This finding is consistent with studies showing that genetically heat-tolerant dairy cows exhibit better physiological adaptation under heat stress (Jensen et al., 2022) and improved temperature regulation compared with conventional Holsteins (Carmickle et al., 2022). The novelty of this study lies in applying these thermotolerance characteristics to predict milk-production stability under tropical smallholder conditions. When translated to a representative herd of 10 lactating cows, the modeled difference becomes operationally relevant. Under severe heat exposure, the predicted output reaches 72.8 L/day for slick dairy cows compared with 63.6 L/day for non-slick dairy cows, equivalent to an additional 9.2 L/day or approximately 276 L over a 30-day period. This herd-level difference illustrates how biological heat resilience may translate into a measurable production advantage for smallholder dairy enterprises.

The model also identifies THI as a moderating variable that strengthens the productive advantage of slick genetics under increasing heat stress. The production gap increased from 0.84 to 0.92 L/cow/day, while the interaction coefficient (+0.0041) indicates that slick dairy cows experience a less severe production decline than non-slick dairy cows. Recent studies similarly reported that cumulative THI improves milk-yield prediction and that physiological responses vary across lactation stages (Hasan et al., 2025; Tu et al., 2025). However, this study extends previous research by explicitly integrating the interaction between slick genetics and THI within a quantitative predictive model. From an economic perspective, the increasing production advantage under higher THI suggests that slick genetics may contribute to maintaining milk-derived income during periods of thermal stress. At the representative scale of 10 lactating cows, the additional predicted milk output may also improve feed-cost efficiency per liter of milk and reduce the relative dependence on capital- and energy-intensive cooling measures such as fans, blowers, and sprinklers. Because thermotolerance is genetically embedded and can be transmitted through breeding, its potential economic benefit may extend across multiple production cycles, although this advantage must ultimately be weighed against the costs of genetic acquisition, breeding, and herd replacement. These economic implications remain scenario-based rather than confirmed profitability effects because actual milk prices, feed intake and costs, genetic-acquisition expenses, cooling costs, and other farm-level expenditures were not directly measured in the present study.

The relatively low calibration values (R^2 = 0.124 for morning production and R^2 = 0.077 for afternoon production) indicate that THI alone cannot explain the complexity of milk production. Other factors, including parity, lactation stage, nutrition, housing, and health status, also contribute substantially to production performance, consistent with previous findings (Imrich et al., 2021; Džermeikaitė et al., 2025). To isolate the effects of genetics and environmental heat load, these variables were held constant in the simulation. Consequently, the proposed model should be interpreted as a theoretical framework requiring further validation using longitudinal field observations. The same limitation applies to the economic predictions. Milk price, feed expenditure, cooling-equipment cost, electricity consumption, maintenance requirements, and greenhouse-gas emissions were not measured directly; therefore, the economic outputs should be interpreted as scenario-based decision-support indicators rather than observed profitability estimates.

From a practical perspective, slick genetics offers a promising long-term adaptation strategy for lowland dairy systems where cooling infrastructure remains limited. Nevertheless, genetic thermotolerance should complement rather than replace management practices such as adequate shade, ventilation, water supply, nutrition, and animal health programs. Previous studies also recommend integrating genetic selection with environmental adaptation and sustainable breeding programs to improve climate resilience (Cartwright et al., 2023; Camargo et al., 2022). The management relevance of slick genetics can therefore also be evaluated against alternative heat-mitigation investments such as fans, blowers, sprinklers, and improved ventilation. Conventional cooling systems involve capital expenditure, electricity consumption, and maintenance costs, whereas genetic thermotolerance is embedded in the animal and may provide recurring benefits across production periods. The present model does not demonstrate that slick genetics can replace mechanical cooling, but it provides a framework for comparing the value of additional milk output with the annualized cost of cooling infrastructure.

A further implication concerns carbon efficiency. Because emission intensity is commonly expressed as greenhouse-gas emissions per unit of milk output, maintaining higher production under similar management conditions may reduce emissions per unit of product even when total farm emissions do not decline proportionally. Under the severe-THI simulation, the higher milk output of slick dairy cows indicates a potential improvement in emission intensity relative to non-slick dairy cows. However, this should not be interpreted as direct evidence of lower methane or total farm emissions because feed intake, manure emissions, electricity use, and cooling-energy demand were not empirically measured. Future studies should therefore integrate tCO_2e-

based farm inventories with milk-output, cost, and energy data to evaluate the economic value of carbon-efficiency improvements.

Accordingly, the proposed framework provides a basis for future field validation of climate-resilient dairy breeding strategies in lowland regions of Java. By integrating production stability with feed efficiency, cooling-investment considerations, and emission intensity, the framework also extends the relevance of slick genetics from a biological adaptation strategy to a broader management and business-intelligence decision for smallholder dairy systems.

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that slick hair genetics has promising predictive potential to improve milk-production stability under increasing THI conditions in lowland smallholder dairy systems in Java. The simulation showed that milk production declined in both genetic groups as THI increased, but the reduction was smaller in slick dairy cows than in non-slick dairy cows, at 8.04% and 10.11%, respectively. The positive interaction between slick genetics and THI indicates that thermotolerant genetics may buffer part of the adverse effect of environmental heat load. At the representative scale of 10 lactating cows, this advantage corresponds to approximately 9.2 L of additional milk per day, or 276 L over 30 days under severe THI conditions, indicating potential benefits for milk-output stability, feed-cost efficiency, and reduced dependence on intensive cooling investments such as fans or blowers. Higher milk output under comparable production conditions may also improve greenhouse-gas emission intensity per unit of milk. However, slick genetics does not eliminate heat stress and should therefore be interpreted as a complementary adaptation strategy rather than a substitute for adequate farm management. Dairy-development strategies in Indonesia should consider incorporating verified slick-associated traits into long-term breeding programs, particularly for lowland and coastal production environments, while maintaining sufficient drinking water, shade, ventilation, balanced feeding, appropriate housing, and animal-health management. Because the present findings were generated from literature-calibrated simulations, the predicted economic, operational, and carbon-efficiency benefits should be validated using local longitudinal data that include milk prices, feed costs, cooling and energy expenditures, and tCO_2e-based emission measurements before operational breeding or policy decisions are made.

FURTHER STUDY

Future research should empirically validate the proposed THI-moderated model through longitudinal observations in lowland areas of West Java, Central Java, and East Java. Studies should include genetically verified dairy cows, repeated temperature and humidity measurements, daily milk-yield records, rectal temperature, respiration rate, feed intake, parity, lactation stage, and housing conditions. Mixed-effects regression, nonlinear threshold analysis, and cross-validation are recommended to estimate the interaction between slick genetics and THI, identify critical heat-stress thresholds, and evaluate predictive accuracy using RMSE, MAE, and explained variance. Regional comparisons should also be conducted to determine whether the productive advantage of slick genetics differs between northern and southern coastal environments.

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