Research Article

Declining Efficiency and Unequal Access: A District-Level Evaluation of South Sulawesi's Artificial Insemination Program

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Abstract | This study evaluated the performance of the AI program in South Sulawesi Province between 2020 and 2024, focusing on temporal dynamics, structural differences across districts, and institutional capacity. Secondary district-level statistics (2020–2024) were harmonized and analyzed at both provincial and district scales. Districts were classified into quartiles based on productive female populations to enable structural comparisons. Program outcomes were assessed using indicators of farmer participation (acceptor rate, service coverage), reproductive efficiency (conception rate, service per conception), productivity per acceptor (calves per acceptor), and institutional capacity (inseminator workload). Descriptive analysis, one-way ANOVA with Tukey's post-hoc test ($p < 0.05$), and heatmap visualization were applied to reveal inter-district disparities and spatial distribution patterns. Farmer participation and productivity were highest in mid-scale districts, whereas small and large districts consistently underperformed. Provincial trends revealed declining conception rates and increasing service-per-conception ratios, indicating reduced technical efficiency. This decline appears to be driven by uneven inseminator workloads, weakened farmer compliance with estrus detection, and management or nutritional deficiencies in smallholder herds. Inseminator workload was unevenly distributed, with cattle-dense districts heavily burdened while others were underutilized. Calves per acceptor confirmed that household-level benefits were concentrated where adoption and efficiency aligned. The findings demonstrate that AI expansion alone is insufficient to ensure equity and efficiency. Differentiated strategies are needed: improving access in small districts, reinforcing farmer training in mid-scale districts, and addressing technician shortages in large cattle-dense regions through both resource redistribution and renewed investment in recruitment and training. Lessons from India, Brazil, and Kenya highlight that targeted, equity-oriented, and capacity-sensitive interventions can enhance AI's contribution to rural development and livestock-based food security in Indonesia.

Keywords | Artificial Insemination, Reproductive Efficiency, Livestock Policy, Institutional Capacity, South Sulawesi, Case Study

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INTRODUCTION

Artificial Insemination (AI) has been promoted globally as a cornerstone reproductive biotechnology to accelerate genetic improvement, enhance reproductive efficiency, and strengthen livestock productivity in smallholder systems. In developing country contexts, AI is not only a technical intervention but also a socio-economic tool to expand access to improved germplasm, reduce the reliance on natural mating, and contribute to rural livelihoods and food security (FAO, 2018; Mikkola *et al*., 2024).

In Indonesia, AI has been prioritized as part of the broader national agenda to achieve food security. Through the *Asta cita* development framework, the government has emphasized the need to accelerate livestock production as a means of supporting national food security. Cattle breeding programs based on AI play a central role in this effort, providing an avenue for sustainable herd improvement and reducing dependence on imported beef.

Despite substantial investments, the performance of Artificial Insemination (AI) programs remains heterogeneous across regions. Disparities are often attributed to structural factors such as cattle population size, distribution of breeding female cattle, institutional capacity of inseminators, and farmers' willingness to adopt AI services (Neethirajan, 2022; De Vries *et al*., 2023). Provincial- and district-level variations are particularly relevant in South Sulawesi, one of Indonesia's major cattle-producing provinces, where diverse agro-ecological conditions and resource endowments create uneven program outcomes.

However, empirical evidence on the extent of these disparities remains limited. Most evaluations of Indonesia's AI initiatives have focused either at the national level or through case studies at farm scale, leaving a critical gap in understanding intra-provincial heterogeneity. This gap is particularly urgent to address because uneven adoption and efficiency across districts can undermine aggregate program performance, weaken genetic improvement goals, and jeopardize Indonesia's broader cattle self-sufficiency targets. Without systematic analysis that integrates temporal dynamics, quartile-based structural differences, and institutional capacity indicators, policy interventions risk remaining generic rather than tailored to local realities.

Evaluation of Artificial Insemination (AI) program performance typically involves multiple dimensions. Farmer participation is captured through indicators such as acceptor rate and service coverage, which reflect adoption and accessibility. Technical efficiency is gauged through conception rate and service per conception, while productivity outcomes are measured by calving rates and calves per acceptor. In addition, institutional capacity is reflected in inseminator workload, which determines the effectiveness of human resource allocation. These indicators provide an integrative framework to assess AI as both a reproductive and developmental intervention (Pacana and Koerkamp, 2025; Masho *et al*., 2024).

Therefore, this study evaluates the Artificial Insemination (AI) program in South Sulawesi Province between 2020 and 2024 by combining temporal trend analysis with quartile-based comparisons of district-level performance. By classifying districts according to the size of their breeding female cattle populations, the study systematically contrasts outcomes between small- and large-herd regions. This quartile-based classification provides a finer distinction than a simple high–low grouping, allowing intermediate patterns to emerge. Statistical testing and spatial visualization further highlight structural disparities in adoption, efficiency, and institutional capacity. While this study evaluates program performance at the household and district levels, indicators such as calves per acceptor serve as micro-level proxies of reproductive and productive efficiency. When aggregated across districts, these outcomes collectively influence provincial cattle output and contribute to Indonesia's broader objectives of beef self-sufficiency and food sovereignty.

MATERIALS AND METHODS

Data source

This study employed secondary statistical data on the Artificial Insemination (AI) program in South Sulawesi Province, Indonesia, covering the period 2020–2024. District-level datasets were obtained from official livestock statistics published by the provincial livestock services and harmonized to ensure consistency and comparability across years. The extracted variables included total cattle population, female cattle population, breeding female cattle population, number of AI acceptors, number of inseminators, number of AI services (doses delivered), number of pregnancies from AI, and number of calves recorded from AI pregnancies. These indicators are widely applied in livestock reproduction program assessments, particularly in developing-country contexts (Gedefa *et al*., 2025; FAO, 2018).

Before analysis, all district-level datasets obtained from the Provincial Livestock Service were carefully reviewed for consistency and completeness. Annual figures were compared with corresponding data from the Directorate General of Livestock and Animal Health and the Central Bureau of Statistics (BPS) to ensure alignment of definitions and values. Discrepancies or missing records were verified directly through communication with the respective district livestock offices. When inconsistencies were found, we relied on official correction notes or verified reports submitted in the subsequent year.

Most inconsistencies involved mismatched indicator definitions (e.g., confusion between total and breeding female cattle) and occasional transcription errors in annual

AI service counts. Fewer than 5% of district-year records required minor adjustment, all supported by official correction notes.

Data that could not be verified were cross-checked against provincial summaries and adjusted only when documentary justification was available. In addition, district records were standardized into a single reporting format to ensure that the same administrative boundaries and indicator definitions were consistently applied throughout 2020–2024.

Unit of analysis

The analysis was undertaken at two complementary scales. At the provincial level, data were aggregated across all districts to capture temporal dynamics and macro-level performance. At the district level, data were disaggregated to reveal intra-provincial heterogeneity in adoption, service delivery, and institutional capacity. District-level statistics were summarized as five-year means with standard deviations (SD). Districts were ranked by the five-year mean of breeding female cattle (BFC) population which represents the reproductive base and were subsequently classified into quartiles (Q1–Q4). Q1 represented districts with the smallest reproductive bases and Q4 those with the largest, enabling systematic comparison of AI performance across structural herd-size differences.

Indicator construction

Program performance was evaluated using six quantitative indicators reflecting adoption, efficiency, productivity, and institutional capacity. All indicators were calculated annually at the district level using harmonized definitions of breeding female cattle (BFC), acceptors (ACC), AI services (SERV), pregnancies (PREG), calves (CALV), and inseminators (INS). Each acceptor represented a unique breeding female that received at least one AI service within the year, irrespective of the number of insemination attempts.

The acceptor rate (AR) was calculated as the proportion of breeding female cattle that became AI acceptors ($AR = ACC/BFC \times 100$), and service coverage (SCov) represented the ratio of total AI services to breeding female cattle ($SCov = SERV/BFC$). The conception rate (CR) was computed as the percentage of inseminations resulting in confirmed pregnancies ($CR = PREG/SERV \times 100$), while service per conception (S/C) expressed the number of inseminations required per successful conception ($S/C = SERV/PREG$). The calves per acceptor (CPA) was derived as the total number of calves recorded from AI pregnancies divided by the number of AI acceptors ($CPA = CALV/ACC$). Because calving may occur several months after insemination, this indicator serves as a proxy for household-level productivity rather than a strict cohort measure. Finally, the inseminator workload (WL) represented the number of inseminations performed per inseminator ($WL = SERV/INS$).

These standardized formulas ensured comparability of adoption, efficiency, and productivity metrics across districts and years while maintaining internal consistency with national AI performance reporting standards.

Analytical strategy

Temporal dynamics were assessed by tracking provincial-level changes in adoption, efficiency, and reproductive outcomes between 2020 and 2024, with trends visualized through line graphs. District-level disparities were summarized descriptively (mean ± SD) and compared systematically across quartile groups. Statistical differences among quartiles were tested using one-way ANOVA followed by Tukey's HSD post-hoc comparisons, with significance set at $p < 0.05$. To further capture heterogeneity and visualize inter-district similarities, hierarchical clustering and heatmap visualization were applied to five key indicators acceptor rate, service coverage, conception rate, service per conception, and inseminator workload. The clustering was performed using standardized (z-score normalized) values of these indicators to ensure comparability across different measurement scales. The Euclidean distance metric and Ward's linkage method were used to identify groups of districts with similar performance profiles. The resulting clusters were primarily used to inform the heatmap visualization and to highlight inter-district similarity patterns rather than to conduct formal spatial or statistical inference. Comparative interpretation was situated within Indonesia's national AI targets and international evidence on smallholder livestock systems (Hilmiati *et al*., 2024; Firman *et al*., 2023). This triangulation of temporal, statistical, and spatial approaches strengthened the robustness of inference.

Interpretative framework

The interpretation of results integrated technical, socio-economic, and policy dimensions. Social aspects were examined in terms of farmer participation and equity of service access. Economic considerations focused on inseminator allocation efficiency, farmer-level productivity gains, and the contribution of AI-derived calves to household income and provincial cattle supply. Policy implications were derived by linking observed patterns to institutional governance, data quality, and redistributive strategies for human resources. This approach aligns with contemporary livestock socio-economics research that views reproductive technologies not only as technical solutions but also as instruments for rural development and food security (Prajapati *et al*., 2025).

RESULTS

Quartile-based classification of districts

As shown in Table 1, the quartile-based classification of districts based on the mean number of breeding female cattle (2020–2024) revealed distinct differences in population size across regions. Districts in Q4 (Bone, Wajo, Sinjai, Gowa, Bulukumba, Maros) formed the group with the largest populations and represented the main centers of cattle production in the province. Q3 districts (Barru, Enrekang, Pangkep, Soppeng, Sidrap, Takalar) were classified as medium-scale, while Q2 districts (Luwu Utara, Pinrang, Jeneponto, Selayar, Bantaeng, Luwu Timur) had relatively smaller populations. Finally, the Q1 group (Luwu, Tana Toraja, Pare-Pare, Makasar, Palopo, Toraja Utara) comprised the districts with the smallest reproductive bases.

Table 1: Quartile assignment of districts based on average productive female (2020-2024).

District	Breeding female cattle (Mean ± SD)	Quartile
Bone	116025.42 ± 32060.32	4
Wajo	33977.19 ± 12787.01	4
Sinjai	32883.62 ± 8633.90	4
Gowa	30247.80 ± 8688.07	4
Bulukumba	22732.02 ± 1989.22	4
Maros	20357.49 ± 5161.78	4
Barru	16035.39 ± 4365.64	3
Enrekang	14018.14 ± 674.29	3
Pangkep	12032.48 ± 2451.10	3
Soppeng	9928.58 ± 2359.87	3
Sidrap	9178.90 ± 2539.01	3
Takalar	9047.80 ± 3812.62	3
Luwu Utara	8648.52 ± 3195.18	2
Pinrang	8001.13 ± 2094.59	2
Jeneponto	7547.04 ± 2015.97	2
Selayar	6362.38 ± 1501.37	2
Bantaeng	5400.62 ± 313.90	2
Luwu Timur	5052.61 ± 1969.67	2
Luwu	4361.99 ± 1496.24	1
Tana Toraja	2195.44 ± 226.83	1
Pare-Pare	1367.99 ± 353.43	1
Makasar	938.80 ± 60.47	1
Palopo	689.14 ± 254.48	1
Toraja Utara	48.31 ± 21.41	1

Some variation within the Q4 group was acknowledged; however, the quartile classification was retained to maintain balanced representation and comparability across districts. This approach is commonly used in exploratory performance analyses where proportional representation is prioritized over absolute uniformity within groups. Although alternative classifications such as quintiles or density-based groupings were initially explored, they resulted in uneven sample sizes that reduced the robustness of statistical testing. Therefore, the quartile method was retained as the most practical approach to maintain analytical balance and interpretive clarity across district categories.

Provincial trends in AI program performance

As presented in Table 2, the provincial-level summary of core Artificial Insemination (AI) program variables (2020–2024) highlighted clear differences across quartile groups. Districts in Q4, which had the largest populations of breeding female cattle, also showed the highest program scale, with substantially greater numbers of acceptors, AI services, pregnancies, and calvings compared to all other groups. Q3 and Q2 districts represented intermediate levels of program activity, reflecting moderate adoption and reproductive outcomes. In contrast, the Q1 group, composed of districts with the smallest reproductive bases, displayed only minimal program reach, with consistently low numbers of acceptors and outcomes. At the provincial aggregate level, these disparities produced high variability, indicating that program performance was strongly influenced by structural differences in herd size across districts.

Table 2: Provincial Core AI variables (2020-2024).

Quartile	Acceptor	Inseminator	AI service	Pregnancy	Calve
Q1	113.47 ± 56.06	4.70 ± 0.30	139.57 ± 58.83	51.70 ± 34.15	78.53 ± 27.36
Q2	1795.50 ± 726.94	12.57 ± 0.80	2230.60 ± 741.94	848.20 ± 741.88	1221.20 ± 517.33
Q3	2152.17 ± 850.19	15.70 ± 0.30	2534.30 ± 862.37	976.87 ± 805.51	1279.20 ± 607.59
Q4	6599.87 ± 2268.99	39.90 ± 0.09	8249.27 ± 2552.83	2737.27 ±2207.92	4683.77 ± 2203.57
Province	2639.52 ± 4659.38	98.37 ± 23.73	3237.78 ± 5771.62	1188.25 ±2337.58	1823.93 ± 3778.57

As illustrated in Figure 1, the overall performance of the AI program showed a consistent decline across core variables between 2020 and 2024, with reductions observed in the number of acceptors, inseminations, pregnancies, and calvings. This downward trend was particularly pronounced in pregnancies and calvings, reflecting challenges in maintaining reproductive outputs. In parallel, the efficiency indicators presented in Figure 2 reveal a contrasting dynamic: while the conception rate (CR) steadily declined during the study period, the service per conception (S/C) ratio increased sharply, indicating a deterioration in insemination efficiency. Together, these trends highlight both declining participation and weakening reproductive performance within the AI program.

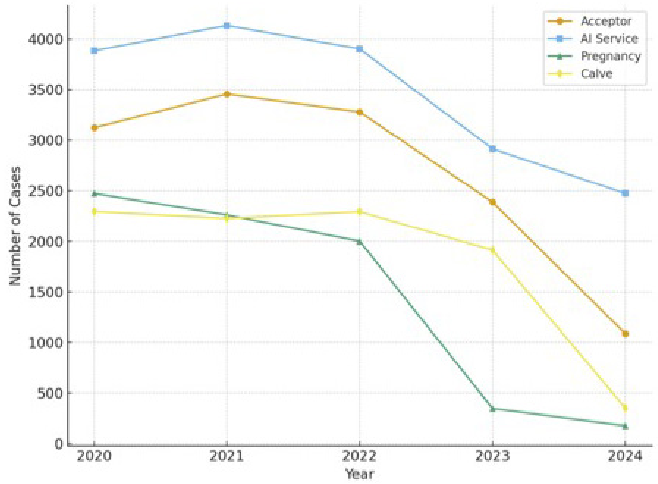

Figure 1: Trends in core AI program variables (2020-2024).

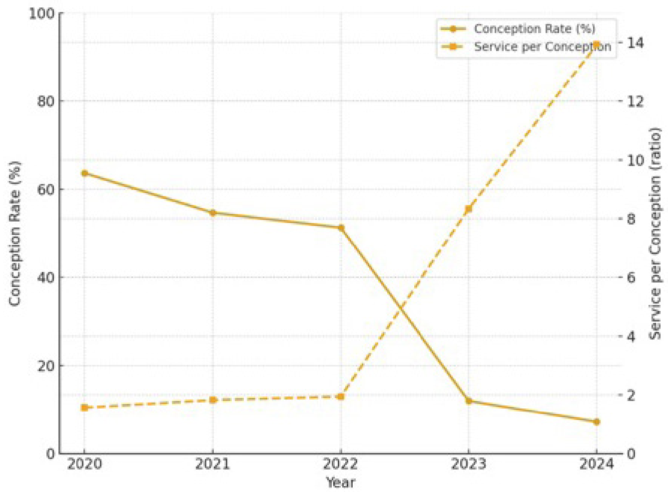

Figure 2: Trends in efficiency indicators: conception rate (CR) and service per conception (2020-2024).

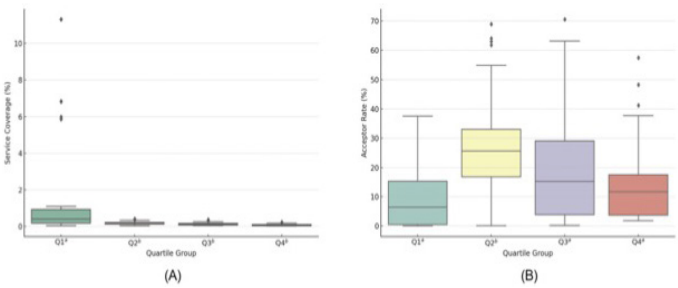

Figure 3: Farmer participation and service coverage by quartile group (2020-2024). (A) Service coverage. (B) Acceptor rate. Different superscripts indicate significant differences among quartiles ($p < 0.05$).

Farmer participation and service coverage

As shown in Figure 3, both service coverage (A) and acceptor rates (B) exhibited differences across quartile groups. Service coverage remained uniformly low, with no statistically significant differences observed ($p > 0.05$). In contrast, acceptor rates varied significantly among quartiles ($p < 0.05$). Districts in Q2 and Q3 showed markedly higher farmer participation compared to Q1 and Q4, indicating that mid-scale populations of breeding female cattle were more engaged with the AI program than the smallest or largest districts.

Reproductive efficiency

As shown in Figure 4, reproductive efficiency indicators varied significantly across quartile groups ($p < 0.05$). Conception rate (Figure 4A) was notably higher in Q4 compared with Q1, Q2, and Q3, reflecting a more favorable reproductive outcome in districts with larger cattle populations. Conversely, service per conception (Figure 4B) showed an opposite pattern, with Q1 requiring substantially more insemination attempts per successful conception compared with Q4. This contrast highlights that regions with smaller female populations (Q1) face greater inefficiencies in reproductive performance, while higher-quartile districts (Q4) demonstrate more efficient AI service delivery and conception outcomes.

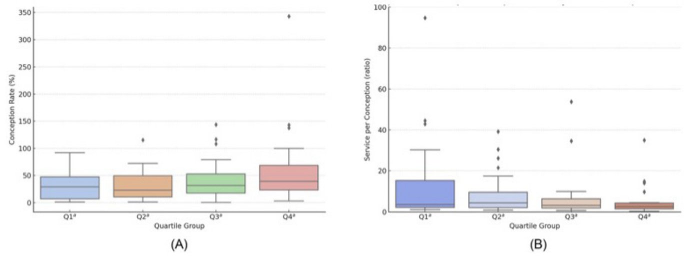

Figure 4: Reproductive Efficiency Indicators by Quartile Group (2020-2024). (A) Conception rate. (B) Service per conception.

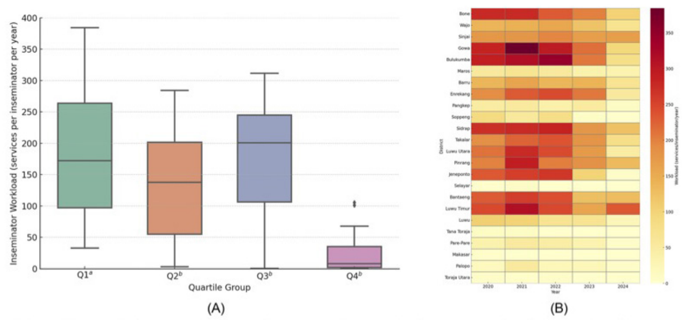

Figure 5: Inseminator workload as an indicator of institutional capacity. (A) Boxplot of services per inseminator across quartile groups (2020-2024). (B) Heatmap of district-level inseminator workload (2020-2024). Different superscripts indicate significant differences among quartiles ($p < 0.05$).

Institutional capacity

As shown in Figure 5A, inseminator workload differed significantly among quartile groups ($p < 0.05$). The median workload was lowest in Q4 districts, reflecting overall lower service loads per inseminator due to higher technician availability in cattle-dense regions. However, the heatmap (Figure 5B) reveals substantial variation within Q4, with certain large-population districts such as Bone, Bulukumba, and Sidrap showing exceptionally high workloads compared to smaller or better-resourced areas such as Selayar, Makassar, and Toraja Utara. This pattern indicates that while workloads are statistically lower on average in Q4, intra-group disparities remain pronounced at the district level, underscoring uneven distribution of inseminator resources.

Productivity outcomes

As presented in Figure 6, calves per acceptor varied significantly among quartile groups ($p < 0.05$). Q1 exhibited higher productivity outcomes compared to Q2, while Q3 showed intermediate values. Interestingly, Q4 displayed more variability, with some districts achieving outlier values above the overall trend. These differences suggest that productivity outcomes are not solely determined by the scale of the program but also by management efficiency and resource allocation within districts.

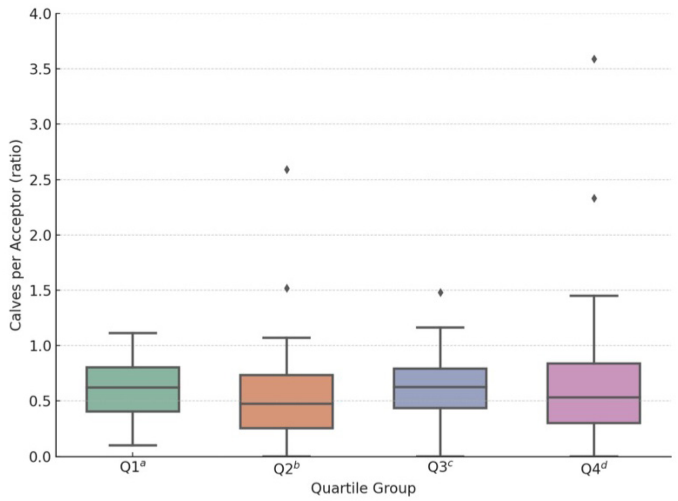

Figure 6: Productivity outcomes represented by calves per acceptor across quartile groups (2020- 2024). Different superscripts indicate significant differences among quartiles ($p < 0.05$).

DISCUSSION

This study provides a comprehensive evaluation of the Artificial Insemination (AI) program in South Sulawesi Province from 2020 to 2024, emphasizing differences in farmer participation, reproductive efficiency, institutional capacity, and productivity outcomes across districts. By combining temporal analysis and quartile-based comparisons, the findings reveal that structural capacity, while important, does not automatically ensure efficiency or equity in AI outcomes.

The quartile-based classification of districts (Table 1) established a clear structural framework for analysis, separating districts into groups based on their breeding female cattle populations. Large-scale districts (Q4) such as Bone, Wajo, and Sinjai emerged as centers of AI activity, while small-scale districts (Q1) such as Toraja Utara and Palopo had far fewer reproductive resources. However, this structural variation did not translate directly into uniform program outcomes, highlighting the importance of institutional and socio-technical factors.

Provincial-level dynamics further underscored these disparities (Table 2; Figure 1). Over the five-year period, the number of acceptors, inseminators, AI services, pregnancies, and calves fluctuated substantially, with a general downward trend in reproductive outcomes. These trends suggest declining program efficiency despite ongoing service provision, a pattern consistent with reports from Indonesian smallholder systems (Wiranto *et al.*, 2020) and similar to findings in Bangladesh where long-term AI expansion faced diminishing efficiency over time (Uddin *et al.*, 2014). It is also important to note that the early phase of the study period (2020–2021) coincided with the COVID-19 pandemic, which temporarily disrupted insemination logistics, field supervision, and farmer extension activities. While these disruptions may have contributed to the initial decline in conception rates, the continuation of the downward trend after 2022 indicates that structural efficiency issues likely extended beyond pandemic-related effects.

The sustained decline in participation and efficiency across 2020–2024 reflects the combined influence of pandemic-related disruptions and underlying institutional constraints. While COVID-19 restrictions initially reduced field supervision, semen distribution, and farmer training, the continued downward trend after 2022 suggests more persistent factors. Limited refreshment training for inseminators, uneven resource allocation, and declining farmer motivation due to repeated conception failures likely compounded these effects. In several districts, delays in insemination scheduling and weak coordination between inseminators and local extension officers were also reported by provincial livestock offices. Comparable multi-factor declines have been observed in Ethiopia and India, where efficiency losses followed large-scale AI program expansions (Tadesse *et al.*, 2022; Panda *et al.*, 2021).

Farmer participation, expressed through service coverage and acceptor rate, revealed systematic differences between quartiles (Table 2; Figure 3). Participation was strongest in mid-scale districts (Q2–Q3), while both small (Q1) and large (Q4) districts lagged significantly. The statistical differences between quartiles ($p < 0.05$) confirm that adoption is not uniformly distributed. Field information from provincial livestock offices indicates that mid-scale districts typically have better road access, more active farmer groups, and closer coordination between inseminators and extension officers, which likely facilitate timely services and farmer engagement. In contrast, small districts often face logistical constraints and limited institutional reach, whereas large districts experience diluted supervision and uneven input delivery. This aligns with Panda *et al.* (2021) in India, who reported that small herds were reluctant adopters due to perceived low benefits, while large herds experienced diluted participation because of overextended institutional capacity. The South Sulawesi case therefore reinforces international evidence that adoption peaks at intermediate scales where service accessibility and farmer incentives are balanced.

Reproductive efficiency indicators (Table 2; Figures 2 and 4) demonstrated further challenges. Conception rate (CR) declined markedly over the study period, while service per conception (S/C) ratios increased, indicating reduced technical efficiency. Between quartile groups, mid-scale districts achieved relatively higher CR and lower S/C values, while small and large districts showed unfavorable efficiency patterns. Statistical testing confirmed significant differences ($p < 0.05$) among groups. These results mirror observations in tropical AI systems, where estrus detection errors, technician fatigue, and nutritional deficits contribute to low conception success (Riaz *et al.*, 2023; Tadesse *et al.*, 2022).

Although the present study did not include direct interviews or field surveys, supporting information from provincial livestock service reports provides context for the declining conception rate. Reduced field supervision frequency, longer semen distribution intervals, and declining participation in inseminator refresher training after 2021 were commonly reported. These institutional and operational constraints likely contributed to technician fatigue and suboptimal estrus detection accuracy among farmers. The concurrent increase in the S/C ratio within this dataset further supports the interpretation that insemination efficiency declined despite continued AI coverage.

Institutional capacity, captured through inseminator workload, highlighted striking disparities between districts (Table 2; Figure 5). The boxplot analysis revealed significantly heavier workloads in cattle-dense districts (Q4), while the heatmap visualization showed stark contrasts at the district level, with Bone and Bulukumba highly burdened while areas such as Selayar and Makassar were underutilized. It should be noted that the association between inseminator workload and reproductive efficiency observed in this study does not imply a direct causal relationship. Rather, it reflects a plausible interaction supported by operational experience in AI programs, where excessive workloads can coincide with lower conception rates due to technician fatigue or delayed service timing. Other contextual factors such as semen storage logistics, cold chain reliability, technician training, and farmer compliance with estrus detection protocols may also contribute to reduced efficiency, particularly in geographically large or remote districts. Therefore, the results should be interpreted as indicative correlations within a complex system of institutional and technical influences, not as evidence of singular causality. This imbalance closely resembles findings in Zambia, where poor inseminator deployment reduced program efficiency (Sianangama *et al.*, 2022), and in India, where overworked technicians negatively influenced conception rates (Singh *et al.*, 2022). International models from Brazil, which implemented workload-based technician redistribution (Da Silva *et al.*, 2024), and from Kenya, where AI service delivery was decentralized into county-level extension systems (Makokha *et al.*, 2020), offer relevant policy lessons for Indonesia.

Productivity outcomes, expressed as calves per acceptor, further illustrated inequities (Table 2; Figure 6). Mid-scale districts (Q2–Q3) achieved the highest average productivity, while small (Q1) and large (Q4) districts performed poorly. The relatively strong performance of mid-scale districts (Q2–Q3) appears to stem from structural and institutional advantages, including moderate cattle population density, better accessibility through local road networks, and more balanced ratios of inseminators to active farmers. These conditions allow for more timely insemination services and closer farmer–technician interactions, resulting in higher conception and productivity rates. The recommendation to reinforce farmer training in these districts aims not to correct deficiencies but to sustain their advantage through updated technical guidance on estrus detection, insemination timing, and post-service management. This pattern indicates that household-level benefits from AI are maximized where adoption and efficiency are jointly optimized. Comparable outcomes were reported in Sri Lanka, where AI improved household income only when inseminator resources were equitably aligned (Paradehiwatta, 2025), and in Ethiopia, where district-level disparities mirrored those observed in South Sulawesi (Temesgen *et al.*, 2021).

Taken together, the results from Tables 1–2 and Figures 1–6 highlight a paradox. South Sulawesi possesses both a large reproductive base and established Artificial Insemination (AI) infrastructure, yet efficiency has declined and benefits are unevenly distributed. Expansion of insemination services alone is insufficient to achieve Indonesia's livestock development goals under the *Asta cita* agenda for food security. Differentiated strategies are required: Q1 districts need improved access through mobile inseminator services and subsidized delivery; Q2–Q3 should be reinforced with farmer training to sustain their comparative advantage; and Q4 requires redistribution of inseminators and systematic workload monitoring.

International experiences provide relevant policy models. India's Rashtriya Gokul Mission improved adoption by introducing subsidized AI services and mobile clinics (Ranjan *et al*., 2025); Brazil's *Progeny testing Program* enhanced efficiency through farmer training and technician redeployment (Pereira *et al*., 2024); and Kenya's decentralized AI governance reduced service disparities between districts (Methu, 2015). Adapting such interventions to Indonesia's provincial contexts would help ensure that AI contributes not only to genetic improvement but also to equitable rural development and national food security.

This study is not without limitations. The use of secondary statistics constrains indicator precision, as district-level reporting may vary in accuracy. Calves per acceptor were derived from aggregate calving records and may not fully distinguish AI-derived births from natural mating. Additionally, farm-level determinants such as feed management, estrus detection skills, and timing of insemination were not captured. Future research should integrate longitudinal farm-level data, reproductive management surveys, and semen quality monitoring to refine efficiency metrics. Comparative studies across provinces would further clarify whether the disparities observed in South Sulawesi reflect broader national trends or are region-specific.

In summary, the systematic comparison across Tables 1–2 and Figures 1–6 demonstrates that Artificial Insemination (AI) in South Sulawesi is constrained by uneven adoption, declining reproductive efficiency, and misaligned institutional capacity. Addressing these issues requires policies that embed AI as an equitable and efficiency-oriented intervention. By learning from international experiences and tailoring solutions to local contexts, Indonesia can enhance AI's role as both a reproductive technology and a strategic instrument for livestock-based food security within the *Asta Cita* framework.

CONCLUSION

This study demonstrates that the performance of the Artificial Insemination (AI) program in South Sulawesi between 2020 and 2024 is shaped not only by herd size but also by institutional and socio-technical dynamics. While large districts possess greater structural capacity, program outcomes remain uneven due to declining conception rates, high service-per-conception ratios, and imbalances in inseminator workload. Mid-scale districts consistently achieved higher adoption, efficiency, and productivity, highlighting the importance of aligning farmer participation with institutional capacity. These findings underscore that AI expansion alone is insufficient to meet Indonesia's *Asta cita* agenda for livestock-based food security; differentiated, context-specific strategies are required. Strengthening access in small districts, consolidating training and reproductive management in mid-scale areas, redistributing inseminator resources in cattle-dense districts may provide short-term relief to workload imbalances but will not be sufficient on its own. Given the overall decline in inseminator numbers and service volume during the study period, long-term improvement will require renewed investment in inseminator recruitment, professional incentives, and continuous training to rebuild institutional capacity. Lessons from international experiences confirm that targeted, equity-oriented, and efficiency-focused interventions can transform AI into both a reproductive biotechnology and a strategic tool for rural development and national food security.

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NOVELTY STATEMENT

This study offers the first district-level assessment of South Sulawesi's AI program that integrates temporal trends with quartile-based structural classification. By simultaneously analyzing adoption, efficiency, productivity, and institutional capacity, the research reveals previously undocumented intra-provincial disparities and demonstrates that declining AI performance is closely linked to mismatches between herd scale and inseminator workload. These findings provide new evidence to guide targeted, district-specific policy interventions.

AUTHOR'S CONTRIBUTION

Ta, AA, MY, SN, and AMD conceived and designed the study. Ta, AA and MY supervised and coordinated the research and provided the data. Statistical analysis was conducted by Ta and AMD. The initial draft of the manuscript was prepared by Ta, AA, MY, and SN. All authors critically reviewed and approved the final version of the manuscript.

Generative AI and AI-assisted technology statement

The authors declare that no Generative AI was used in the creation of this manuscript.

Conflict of interest

The authors declare no conflict of interest with any financial, personal, or other relationships with other people or organizations related to the material discussed in the manuscript.

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