A COMPREHENSIVE REVIEW OF BEEF CATTLE POPULATION DYNAMICS: INSIGHTS FROM ASSESSMENT AND BIBLIOMETRIC EVIDENCE

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ABSTRACT
Beef cattle production is an essential component of food security, particularly in regions where livestock supports nutrition, income, and rural livelihoods. This study examines beef cattle population dynamics by integrating global bibliometric patterns with a qualitative case analysis of Bali Province, aiming to understand how policy, environmental conditions, and market mechanisms interact to shape herd growth and long-term sustainability. Through field observations, semi-structured interviews, document analysis, and bibliometric mapping, the study identifies the ecological, socio-economic, and institutional factors that influence population trajectories at national and regional scales. The findings show that Indonesia's beef cattle population has increased over the past two decades but continues to experience notable fluctuations driven by disease events, environmental stress, market pressures, and shifting policy priorities. In Bali, population changes are more volatile due to movement restrictions, limited genetic inflow, and strong market incentives that affect breeding female retention. The bibliometric analysis highlights an expanding interdisciplinary research landscape, with growing attention to animal physiology, veterinary medicine, genetics, disease ecology, environmental resource management, and production systems. Across scales, the study shows that water availability, forage conditions, disease transmission, reproductive practices, and price dynamics collectively shape herd stability, resilience, and population recovery following shocks. Overall, the study concludes that sustainable beef cattle population development requires a systems-oriented approach that integrates governance, environmental management, animal health, and market coordination. These insights advance understanding of beef cattle population dynamics and provide strategic guidance for strengthening future livestock development and national food security.

KEYWORDS: beef cattle, population, policy, environmental conditions, market mechanisms

1. INTRODUCTION

Beef cattle production constitutes a fundamental component of food security systems, particularly in developing countries where livestock serves as a primary source of animal protein. In Indonesia, cattle contribute significantly to national efforts aimed at ensuring the availability of safe, sufficient, and nutritious meat for a growing population. The country's diverse agroclimatic zones, especially tropical regions with abundant rainfall and sunlight, provide favorable ecological conditions that support continuous forage availability and water resources essential for cattle farming. Within this context, beef cattle breeds raised in Indonesia exhibit adaptive traits suited for efficient slaughter and high-quality meat production, reinforcing their strategic importance in national food systems. Understanding the biological, environmental, and management factors that shape cattle development is therefore central to strengthening food security and livestock sustainability.

Globally, research on cattle development has increasingly emphasized molecular, ecological, and management dimensions. Multi-omics analyses, for example, have been used to characterize rumen microbial dynamics across growth stages, providing insights into metabolic processes that influence cattle performance and productivity [1]. Other studies highlight the relevance of external support, farm management, and producer performance in sustaining cattle-based livelihoods, demonstrating that socio-economic factors play a critical role in livestock development [2]. The influence of environmental and sanitation practices on microbial populations in meat processing environments also underscores the interconnectedness of upstream and downstream production systems [3]. At the production level, reproductive technologies such as artificial insemination rely not only on biological parameters but also on breeder capacity and institutional support, further illustrating the multidimensional nature of cattle population management [4].

In Indonesia, the geographical landscape contributes to diverse livestock development patterns. Bali, located between Java and Lombok, is among the key regions known for its cattle population and long tradition of livestock rearing. The province's strategic position and established agricultural systems support beef cattle production that is essential both for local meat supply and interregional distribution. However, cattle population dynamics in Bali remain influenced by a complex interplay of ecological, socio-economic, and policy factors. Studies on beef cattle systems elsewhere indicate that microbiome-related quality changes during meat storage [5], grazing land management [6] and genetic characteristics of small inbred populations [7] can significantly affect population performance and long-term sustainability. Moreover, the dynamics of pathogens such as Salmonella in harvest-ready cattle [8] toxicokinetic exposure risks from environmental contaminants [9] and policy interventions targeting national beef self-sufficiency [10] further demonstrate the multifactorial considerations in cattle population development. Disease modeling, environmental risk assessments, parasitic prevalence, and tick population studies similarly reinforce the need for region-specific analyses to support effective livestock management [11], [12], [13].

This study seeks to develop a comprehensive and integrative understanding of beef cattle population dynamics in Bali Province by pursuing an analytically rigorous set of objectives that capture the complexity of livestock development in a rapidly evolving agrifood system. Specifically, the research aims to (1) employ a bibliometric analysis to map global and national scientific trajectories related to cattle population management, thereby positioning Bali's case within broader conceptual and methodological trends; (2) examine how government policies and institutional arrangements shape demographic outcomes, production efficiency, and farmer decision-making; (3) assess the influence of key environmental determinants including water availability, climate variability, and disease ecology on population stability and long-term sustainability; (4) analyze market mechanisms such as demand growth, price formation, and the structure of supply chain networks that mediate population movements and production incentives; and (5) integrate these policy, environmental, and market dimensions into a unified analytical framework capable of revealing how multi-level signals interact to influence cattle population growth trajectories, system resilience, and future development pathways.

2. Bibliometric approach

The Boolean search strategy for the topic "Beef Cattle Population Dynamics" combines key species terms and demographic concepts to ensure comprehensive retrieval of relevant literature. The core search string may be structured as: ("beef cattle" OR "beef herd*" OR "beef cow*" OR "beef production system*" OR "Bos taurus" OR "Bos indicus") AND ("population dynamics" OR "population growth" OR "population structure" OR demography OR "herd dynamics" OR "population trend*" OR "population fluctuation*" OR "carrying capacity" OR recruitment OR mortality). This query should be applied to TITLE-ABS-KEY fields in databases such as Scopus or Web of Science, limited to peer-reviewed articles and reviews, and optionally restricted to publications from 2000 onward to ensure contemporary relevance.

Inclusion criteria encompass studies that explicitly analyze beef cattle demographic parameters (e.g., birth rate, mortality rate, culling rate, replacement rate), herd structure, reproductive performance, or population modeling using quantitative or empirical data. Excluded are studies focusing solely on dairy cattle without beef relevance, meat quality or nutrition trials without population-level analysis, wildlife bovines outside production systems, and non-peer-reviewed documents such as conference abstracts or editorials. This framework ensures methodological rigor and thematic alignment with population dynamics in beef production systems.

Figure 1 shows the documents by year in Scopus. Based on the Scopus "Documents by year" chart for the keyword "Beef cattle population dynamics," publication output was modest and variable in the early 2010s about 4 items in 2010, rising to 7 in 2011–2013, followed by a trough around 2015 (3 documents) and a small rebound in 2016 (4). A pronounced upswing began in 2017 with 12 documents, then stabilized at 8–10 per year during 2018–2022. Activity accelerated again thereafter, reaching 15 in 2023, dipping slightly to 13 in 2024, and peaking at 17 in 2025, indicating growing and sustained interest in this topic. The apparent sharp decline to 2 in 2026 almost certainly reflects partial-year indexing rather than a substantive contraction in research output. Overall, the trajectory suggests a maturing field with periodic surges, culminating in a recent high in 2025 after several years of steady productivity.

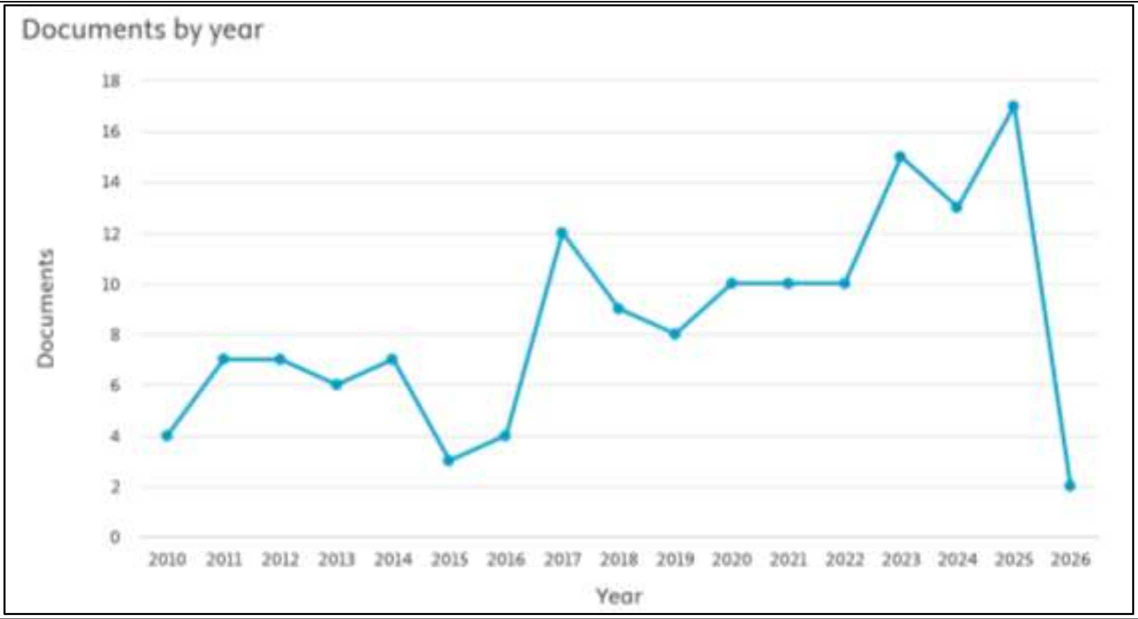

Figure 1. documents by year in Scopus

Figure 2 shows the network visualization in Vosviewer. The VOSviewer network visualization shows a well-connected bibliometric landscape composed of three major clusters green, red, and blue each representing distinct but interrelated thematic areas within the research domain of *beef cattle population dynamics*. The **green cluster** centers heavily on terms such as *population dynamics, cattle, animal, animal husbandry,* and *physiology*, suggesting that this group represents studies focusing on biological, ecological, and demographic aspects of cattle populations. The **red cluster** includes terms like *beef cattle, livestock, prevalence, dairy cattle,* and *veterinary medicine*, indicating a strong emphasis on applied livestock science, production management, epidemiology, and veterinary-related research. Lastly, the **blue cluster** emphasizes *genetics, microbiology, procedures, isolation and purification,* and *bacterium*, reflecting laboratory-based research ranging from genetic analysis to microbial characterization relevant to cattle health and productivity.

The figure 2 shows a dense web of co-occurrences among keywords, illustrating how research topics are strongly interdisciplinary. The term **"animal"** sits centrally, functioning as a semantic bridge between the three clusters, showing its foundational role in studies related to both cattle production and biomedical contexts. Terms such as *cattle, bovine,* and *nonhuman* also appear near the network's center, revealing their frequent co-appearance across fields, from agricultural science to veterinary health research. Meanwhile, cross-cluster connections such as those linking *population dynamics* (green) to *beef cattle* (red) or *genetics* (blue) highlight how population studies increasingly incorporate genetic and health-related factors. This interconnectedness suggests that modern research on beef cattle no longer looks solely at production but integrates biological, epidemiological, and molecular perspectives.

Overall, the network indicates a maturing and multidisciplinary research field where **beef cattle population dynamics** is influenced by broader themes such as animal physiology, herd management, biotechnology, and disease surveillance. The presence of keywords like *controlled study, animal experiment,* and *procedures* suggests that experimental and evidence-based approaches are increasingly used to understand population-level outcomes. At the same time, the strong visibility of *veterinary medicine* and *prevalence* underscores ongoing efforts to link population dynamics with animal health and disease control strategies. Taken together, this bibliometric map shows that research on beef cattle populations is expanding from traditional demographic studies toward a more holistic approach that integrates genetics, microbiology, production systems, and veterinary science.

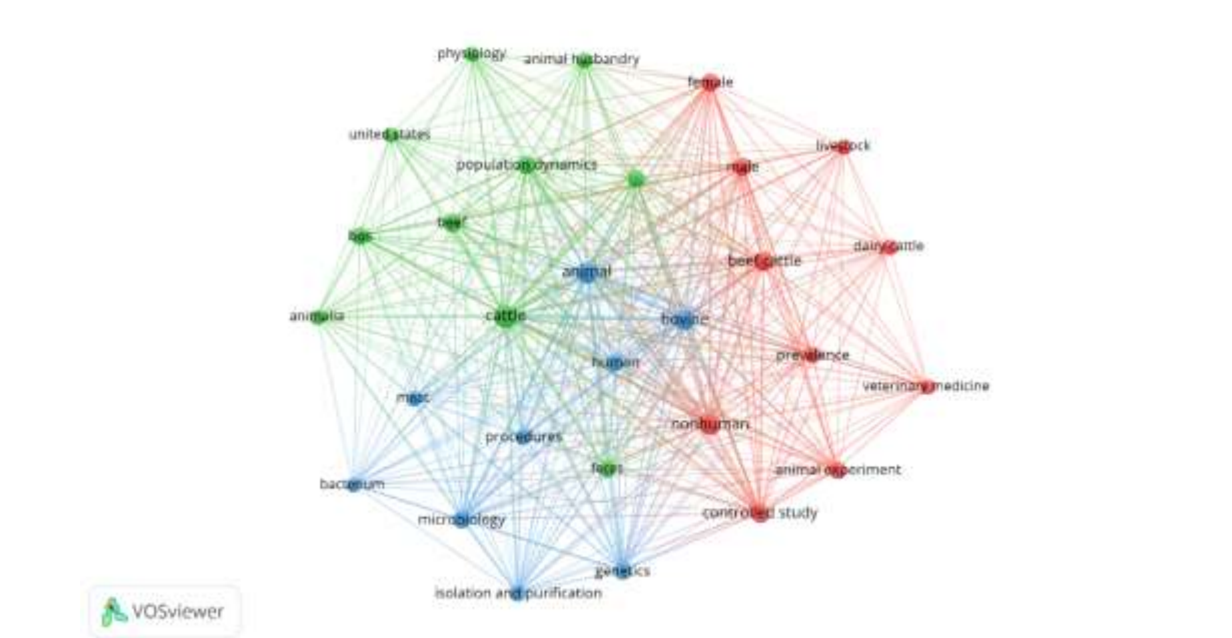

Figure 2. Network visualization in Vosviewer

The first keyword is **animal experiment** which emerged and is interesting to research in 2020 and beyond as shown in figure 3. The results indicate that beef cattle population dynamics are governed by a complex interaction of environmental, biological, and management-related factors. Simulation-based and mechanistic modeling approaches demonstrated that resource availability, particularly water and feed, plays a decisive role in shaping population trajectories. Dynamic modeling of water footprint revealed temporal variability across production stages, with resource constraints inducing oscillatory population behavior under scarcity conditions [14]. Similarly, system-based simulations of grazing land and biomass utilization confirmed that adaptive management strategies such as optimizing land use and integrating agricultural by-products significantly improve production stability and sustainability [6], [15]. These findings are consistent with studies highlighting the importance of feed composition and rumen microbial dynamics in determining growth efficiency and metabolic performance in cattle [1], [16], [17]. Furthermore, reproductive interventions, particularly artificial insemination, were shown to enhance herd expansion and genetic improvement when supported by institutional and farmer-level capacities [4] aligning with broader evidence on the role of genetic selection in improving productivity and population resilience [18], [19].

Health-related factors emerged as critical determinants of population sustainability, with disease dynamics exerting both direct and indirect effects on productivity. Epidemiological and microbiological studies revealed that pathogens such as *Salmonella enterica*, gastrointestinal parasites, and endemic diseases significantly influence herd performance and mortality rates [8], [12], [20]. Modeling approaches further demonstrated that effective intervention strategies, including biosecurity measures and targeted treatment protocols, can mitigate disease spread within herds [11] while sanitation and environmental control reduce microbial risks across the production chain [3]. Additionally, emerging and re-emerging diseases, including foot-and-mouth disease and zoonotic infections, underscore the importance of spatiotemporal surveillance and integrated health management systems [21], [22], [23]. From an environmental perspective, unsustainable production practices were associated with increased greenhouse gas emissions and nutrient imbalances, particularly nitrogen flows, highlighting the need for improved resource efficiency and ecological stewardship [24], [25]. Economic and policy-related factors also significantly influenced population dynamics, as market access, price signals, and policy interventions determined farmers' investment capacity and production decisions [26]. In developing contexts, external support systems and institutional frameworks were shown to enhance farm performance and sustainability, particularly among smallholder producers [2], [27] Collectively, these results emphasize that sustainable beef cattle production requires an integrated systems approach that simultaneously addresses resource management, animal health, genetic improvement, and socio-economic drivers to ensure long-term resilience and productivity.

The second keyword is **veterinary medicine** which emerged and is interesting to research in 2020 and beyond as shown in figure 3. The findings of this study highlight the central role of veterinary medicine in shaping beef cattle population dynamics through its influence on disease control, herd management, and productivity outcomes. Endemic infectious diseases such as Bovine Viral Diarrhea and Bovine Tuberculosis remain critical constraints to population stability, as they elevate mortality, reduce reproductive success, and increase involuntary culling, thereby disrupting long-term herd structure. These impacts are consistent with mathematical and epidemiological studies demonstrating that disease dynamics interact strongly with demographic parameters and cattle movement networks to determine transmission persistence and outbreak magnitude [11], [21]. Age-structured and within-herd models have further shown that targeted interventions such as improved biosecurity, culling of persistently infected animals, vaccination, and farm-level sanitation are effective in mitigating disease spread and maintaining herd integrity [3], [11]. The integration of veterinary science with dynamic modeling frameworks thus provides a robust platform for forecasting disease behavior and optimizing intervention strategies to minimize productivity losses.

Beyond infectious diseases, the results demonstrate that genetic diversity and broader environmental and management factors significantly affect cattle population resilience. Maintaining genomic variation increases adaptive capacity and disease resistance, whereas intense selection without structured breeding management can result in reduced fitness, as shown in studies of inbred or regionally specialized beef cattle populations [7], [19]. Advancements in genomics and multi-omics approaches have enhanced understanding of microbial, metabolic, and physiological processes that contribute to growth performance and overall herd productivity [1], [17]. Likewise, dietary composition and rumen microbial dynamics are central to animal health and feed efficiency, reinforcing the interconnectedness of nutrition, microbiome stability, and demographic performance [16], [28]. These scientific developments provide evidence that cattle population sustainability is underpinned by a combination of genetic, nutritional, and physiological determinants, each shaped by veterinary oversight and management decisions.

Socio-economic conditions further influence the capacity of farmers particularly smallholders to maintain stable cattle populations. Market conditions, production costs, policy frameworks, and access to veterinary services determine farmers' ability to invest in improved management and disease prevention. Empirical studies show that external institutional support, policy incentives, and community-level programs significantly enhance farmers' willingness and ability to sustain cattle production systems [2], [10]. Simulation-based and systems-dynamics research in various regions has also illustrated that land management, resource availability, and environmental constraints directly shape herd growth trajectories and carrying capacity [6], [15]. As veterinary services improve herd health by reducing morbidity and mortality and supporting reproductive performance, they contribute directly to the economic viability of cattle operations, reinforcing the multi-layered interactions between health, productivity, and livelihoods. Collectively, these findings emphasize the need for a multidisciplinary framework that integrates veterinary medicine, genetics, epidemiology, and socio-economic considerations to ensure resilient and sustainable beef cattle production systems.

The third keyword is **dairy cattle** which emerged and is interesting to research in 2020 and beyond as shown in **figure 3**. The comparative analysis of dairy and beef production systems consistently demonstrates that the two sectors operate under distinct demographic, economic, and biological pressures. Dairy farms typically employ intensive management aimed at maximizing milk output, resulting in greater susceptibility to production-limiting diseases such as bovine ephemeral fever and paratuberculosis, both of which can impose substantial economic burdens on high-input operations [11], [29]. In contrast, beef systems are shaped more strongly by environmental heterogeneity, market-driven carcass traits, and broader grazing land dynamics, as shown in Ethiopia, Canada, and Indonesia, where resource availability, herd structure, and pricing mechanisms reflect region-specific production goals [26], [30], [31], [32]. Crossbreeding initiatives contribute significantly to productivity gains, with evidence from Kazakhstan showing that incorporating specialized beef genotypes (e.g., Aberdeen Angus) enhances growth and carcass traits, supporting the argument that genetic integration across dairy and beef lines can yield synergistic performance benefits [18].

Health challenges also differ markedly between the sectors, with beef herds often experiencing higher exposure to endemic parasites, vector-borne diseases, and environmental contamination. Studies across tropical and temperate regions reveal substantial burdens of gastrointestinal nematodes, ticks, and endoparasites in calves and grazing cattle, underscoring the importance of climate-responsive and breed-specific parasite control strategies [12], [13], [20]. Wildlife interfaces such as Leptospira interrogans spillover from bats and the persistence of pathogens like Chlamydia pecorum in apparently healthy cattle further emphasize the complexity of disease ecology in extensive systems [33]. Meanwhile, microbiome-based insights highlight how diet, life stage, and environmental conditions shape rumen and gut microbial communities, influencing growth efficiency, reproductive success, and overall herd resilience [16], [17]. These findings support targeted feeding strategies, early-life microbiome modulation, and environmental hygiene interventions as cross-cutting tools for improving herd health in both dairy and beef operations.

Food safety and sustainability considerations extend beyond the farm, with several post-harvest studies demonstrating the importance of sanitation, predictive microbiology, and packaging integrity in maintaining beef quality and minimizing spoilage. Machine learning applications have proven effective in anticipating blown-pack events in vacuum-packaged beef and identifying contamination drivers of persistent organic pollutants, offering valuable risk-management tools for the meat supply chain [5], [34]. At the same time, landscape-scale models of grazing productivity, water use, and nitrogen flows highlight the need for integrated resource management, including nutrient redistribution, waste-to-fertilizer innovations, and climate-aware stocking decisions, particularly in beef-dominated regions [25], [35], [36]. Policy interventions, gender-inclusive capacity building, and the strategic use of local feed resources such as oil palm biomass further emerge as essential pathways for strengthening self-sufficiency, improving equity in cattle farming, and enhancing long-term sustainability across both dairy and beef sectors [15], [27], [37].

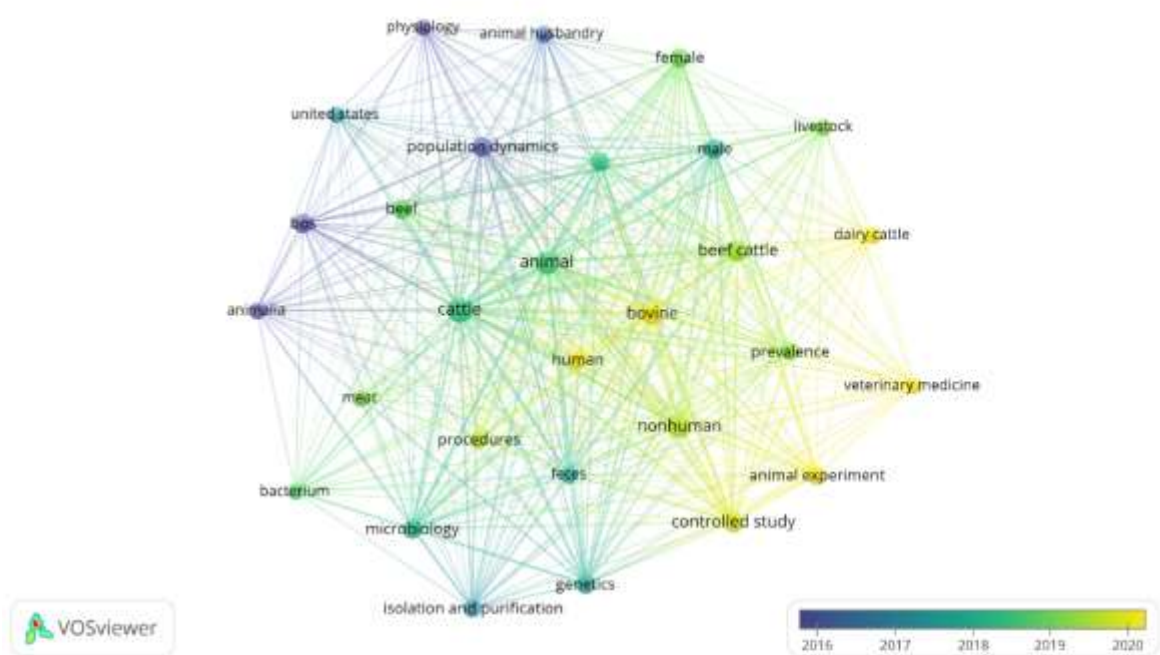

Figure 2. Overlay visualization in Vosviewer

3. METHOD WITH CASE STUDY

3.1 Research Design

This study employed a qualitative research design with a descriptive approach to examine the dynamics of the beef cattle population in Bali Province. Qualitative methodologies emphasize meaning, context, and depth by positioning the researcher as the primary research instrument. Such an approach is well aligned with livestock studies that require contextual interpretation of production systems, management practices, and socio-economic factors influencing herd development elements similarly investigated in cattle research through descriptive surveys, cross-sectional studies, and system-level analyses [38], [39]. The descriptive orientation of this study supports exploratory understanding, consistent with previous work assessing cattle population trends, supply chain characteristics, and production system performance across diverse regional environments [40], [41].

3.2 Data Collection Procedures

Data collection was conducted through three primary techniques: field observations, semi-structured interviews, and document analysis. Field observations were used to directly assess the conditions of beef cattle populations in Bali Province, enabling contextual interpretation of herd characteristics and management practices. The use of on-site observations is supported in the livestock literature, particularly where researchers aim to understand production constraints, environmental conditions, or herd-level dynamics, as demonstrated in simulation-based and ecological assessments of cattle systems in Brazil and Australia [42], [43].

Semi-structured interviews were conducted with breeders, agricultural extension workers, and relevant institutional stakeholders to obtain detailed insights into population dynamics, reproductive management, market access, and policy impacts. This approach aligns with qualitative livestock studies that rely on stakeholder engagement to capture behavioral, economic, and institutional factors shaping cattle production systems [39], [44]. Interviews provided information on breeding practices such as artificial insemination, a factor shown to influence population growth and productivity in various Indonesian cattle systems [45].

The third data source consisted of document studies including historical population records, policy documents, and regulatory frameworks. Document review is commonly used in cattle sector research to contextualize herd-level trends with broader economic and policy interventions, as shown in analyses of self-sufficiency programs, corruption impacts on livestock recovery, and national sustainability agendas [46]. These documents provided longitudinal and institutional perspectives necessary for interpreting population changes in Bali Province.

3.3 Data Analysis

Data analysis followed three systematic stages: data reduction, data presentation, and conclusion drawing. In the reduction stage, raw data collected from observations, interviews, and documents were organized, categorized, and refined to identify information directly relevant to the study objectives. This is consistent with qualitative analytic frameworks used to interpret complex cattle production data, including herd-level disease modeling and market analyses, where filtering and thematic coding are essential for managing heterogeneous datasets [26], [47].

During data presentation, the reduced data were arranged into a coherent structure to facilitate interpretation. Visual and thematic presentation approaches reflect best practices in livestock systems research, where structured data displays support analysis of cattle population trends, production system differences, and environmental sustainability indicators [14], [48].

The final stage involved drawing conclusions based on the interpreted data, leading to an integrated understanding of beef cattle population dynamics and contributing factors in Bali Province. This process parallels analytical strategies employed in regional and national studies assessing cattle growth trajectories, production system sustainability, and policy impacts on herd development [44], [49]. Through these stages, the study generated a descriptive yet analytically rigorous account of the factors shaping cattle population trends within the study area.

4. RESULTS AND DISCUSSION

4.1 National population dynamics (Indonesia, 2000–2022)

Figure 1 shows The Beef cattle population in Indonesia every years. The national beef cattle population series exhibits an overall rising trajectory from ~11.0 million head (2000) to ~17.6–18.6 million head by 2022, punctuated by marked year-to-year volatility. After modest gains through the early 2000s, the population accelerated from 2008, peaking near 16.0 million in 2012 before a sharp contraction in 2013 (~12.7 million), followed by recovery and sustained growth through 2021–2022. Such structural fluctuations are consistent with exogenous shocks and policy-market interactions: (i) disease and biosecurity events can depress inventories through elevated mortality and movement restrictions (e.g., transboundary and emerging diseases) [Menezes et al., 2023; Ahmed et al., 2025]; (ii) supply chain frictions and import-substitution policies can shift culling/breeding incentives and slaughter timing [15], [50]; and (iii) environmental variability (water deficits/drought) alters pasture biomass and liveweight trajectories, affecting offtake and retention rates [51].

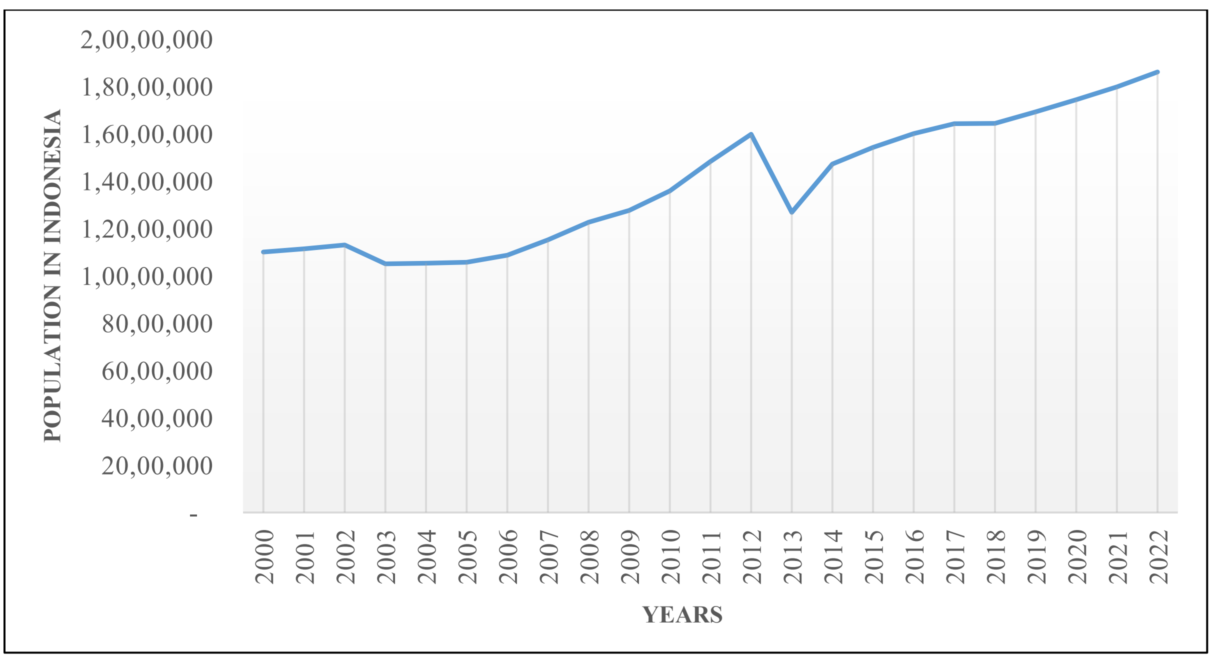

Figure 1. The Beef cattle population in Indonesia

4.2 Provincial population dynamics (Bali, 2000–2022)

Figure 2 shows the beef cattle population in Bali province. Bali's population path differs in amplitude and timing. From 2000 (~529,074 head) to 2012 (~651,216 head), the herd grew with modest annual oscillations (≤~8%), but experienced an abrupt drop in 2013 (~478,146 head). The series rebounded in 2014 (~553,582), with incremental gains to 2016, then fluctuated and fell sharply to ~380,559 by 2022. The inflection points align with (i) island-specific movement restrictions (e.g., prohibitions on non-Balinese cattle entry) that limit genetic inflow and restocking flexibility; and (ii) strong market pull for Bali cattle that can elevate slaughter of breeding females during price spikes, reducing reproductive base stock [40]. Environmental and animal-health pressures (e.g., seasonal trematodiasis dynamics in humid zones; episodic disease events) plausibly compounded these shifts by affecting fertility, calf survival, and sale timing [52].

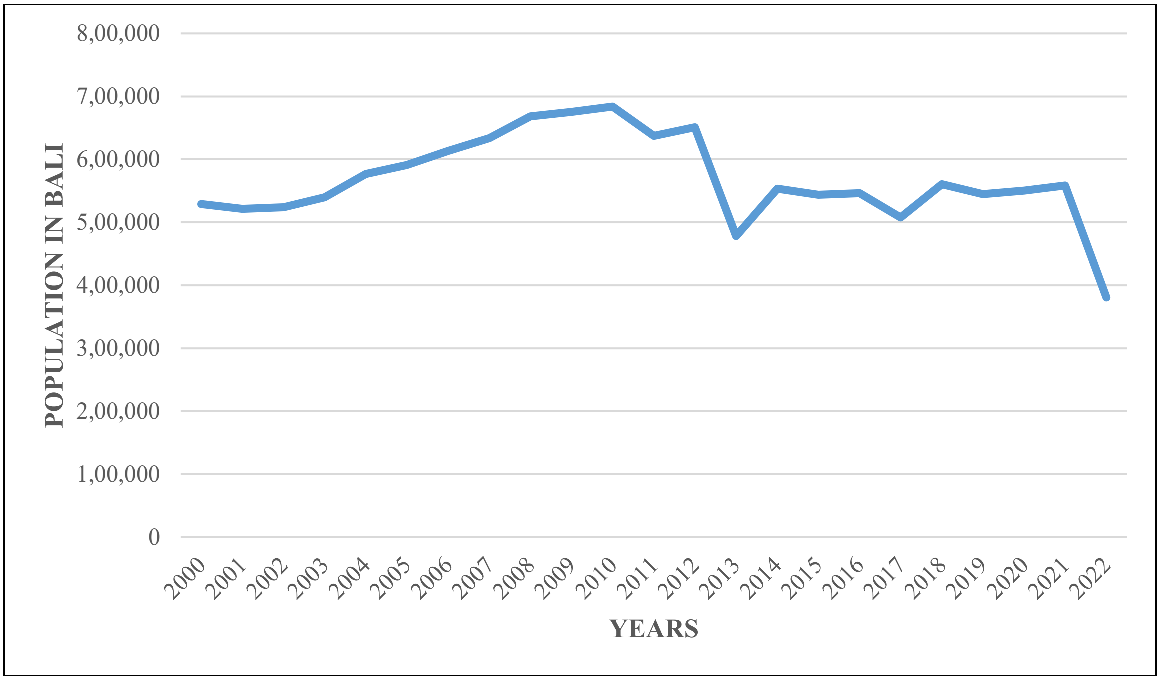

Figure 2. Beef cattle population in Bali province

4.3 Cross-cutting signals from the data

Across scales, three drivers recur: (1) policy and governance self-sufficiency targets, movement rules, and institutional quality influence breeding decisions, movements, and compliance; (2) environmental factors water scarcity and drought propagate through pasture and weight gain to inventories; and (3) market demand price formation and downstream logistics shape slaughter pressure and restocking. These patterns reflect international evidence linking cattle population dynamics to multi-level governance, climate variability, and demand-side shocks [30], [53].

4.4 Government policies and institutional context

The national upswing, despite periodic contractions, is consistent with periods of policy-led expansion aimed at reducing import dependency and stabilizing domestic supply. Econometric assessments of Indonesia's beef self-sufficiency policy indicate that incentives, credit access, and coordinated investments can elevate herd growth but may also transmit volatility if not aligned with regional carrying capacity and market signals [40]. At the meso-level, institutional quality and anti-corruption efforts are associated with more resilient livestock recovery and better allocation of public resources mechanisms that can reduce leakage, improve breeding stock retention, and enhance program credibility [46], [50]. For Bali, movement restrictions (e.g., barring entry of non-Balinese cattle) likely preserved genetic identity but constrained rapid restocking after shocks, rendering the provincial herd more sensitive to demand surges and health events. Comparable policy trade-offs are reported where sanitary measures and identity preservation intersect with market access and restocking logistics [54], [55]. Looking forward, policy designs that combine genetic improvement within breed-identity frameworks (e.g., planned nucleus herds and AI services) and adaptive movement permitting under strict biosecurity could help stabilize breeding female inventories without compromising biosecurity.

4.5 Environmental factors: water, climate variability, and disease ecology

Environmental constraints propagate through forage supply, liveweight gains, and reproductive performance. Mechanistic and accounting-based assessments show that water availability and timing materially affect grazing capacity and production, implying that interannual drought can trigger both emergency offtake and delayed restocking [51]. Drought impacts are not limited to the ranch gate; they cascade along value chains, amplifying price and throughput volatility (e.g., U.S. evidence), a dynamic that mirrors inventory swings seen in Indonesia's series [31]. On the health side, seasonal transmission of Fasciola gigantica in humid settings reduces weight gain and fertility, potentially depressing effective herd growth and pushing producers to liquidate stock during high-risk seasons [52]. Episodic and re-emerging diseases such as lumpy skin disease (LSD) in Asia and other transboundary threats can induce sharp, short-run contractions via morbidity/mortality, movement bans, and market caution. Environmental governance also intersects with climate mitigation commitments: intensification pathways that raise productivity per hectare while decoupling from land conversion can reduce emissions intensity and buffer herds against climate-driven feed constraints [56].

4.6 Market demand, price formation, and supply chain organization
The national and Bali-specific fluctuations are consistent with periods of strong demand and tight supply that elevate slaughter of breeding females, followed by recovery phases as prices normalize. Hedonic analyses of wholesale cattle markets demonstrate that liveweight, age, and condition premiums transmit demand signals that influence on-farm retention decisions; in thin or constrained restocking environments, these signals can erode the breeding base and accentuate volatility [57], [58]. Cross-commodity interactions further shape red meat prices; evidence from Turkey shows that dairy sector dynamics (milk-beef linkages) can propagate into beef price cycles, affecting offtake decisions in mixed systems [53]. Supply chain organization and logistics (cold chain, market access, cooperative coordination) modulate how demand shocks translate into producer behavior; strategic value-creation plans and chain upgrading can improve throughput stability and reduce involuntary culling during price spikes [59]. Producer perceptions of "sustainable beef" also matter; where markets reward sustainability attributes, producers report greater willingness to invest in adaptive practices (e.g., drought planning, biosecurity), with potential to dampen boom-bust cycles in inventories [30].

4.7 Integrating policy, environment, and market signals
The 2013 national contraction and the 2022 Bali decline can be interpreted as stress tests at the intersection of policy constraints, environmental pressure, and demand surges. In such episodes, restricted inflows (policy), depressed carrying capacity or health shocks (environment), and elevated prices (market) align to reduce breeding female retention and delay restocking. International evidence suggests three levers to increase stability: (i) adaptive policy frameworks that maintain breed identity/biosecurity while enabling rapid, verified restocking post-shock [46]; (ii) environmental risk management via water-smart grazing, drought early-warning, and targeted health control for seasonal/epidemic diseases [51]; and (iii) demand side and chain coordination (price risk tools, contract arrangements, and logistics upgrading) to discourage liquidation of breeding stock during temporary price spikes [57].

4.8 Implications for Bali and Indonesia
For Bali, movement restrictions should be complemented by: (a) structured genetic improvement within the local breed; (b) contingency restocking protocols under audited biosecurity; and (c) seasonal parasite control and feed planning tuned to hydrometeorological forecasts [52]. Nationally, aligning self-sufficiency targets with water/climate constraints and market realities through dynamic stocking models, drought insurance, and targeted reproductive programs can raise the effective growth rate of herds and reduce volatility [30], [51] . In both contexts, improving smallholder market participation and productivity (nutrition, reproduction, animal health) remains foundational to meeting rising demand without eroding the breeding base [39].

5. CONCLUSION
This study provides a comprehensive and integrative assessment of beef cattle population dynamics by combining bibliometric evidence with a qualitative case study of Bali Province. The results reveal that cattle population trajectories at both national and regional levels are shaped by a multifaceted interaction of policy frameworks, environmental conditions, market forces, and herd-level health and management practices. Nationally, Indonesia's beef cattle population shows long-term growth despite periodic contractions linked to disease events, supply chain disruptions, and external policy shocks. In Bali, however, the trends exhibit sharper fluctuations due to island-specific constraints such as movement restrictions, limited genetic inflow, and heightened sensitivity to market pressures on breeding females.

The bibliometric analysis underscores the evolution of the scientific discourse toward increasingly interdisciplinary approaches, integrating veterinary medicine, genetics, environmental science, epidemiology, and socio-economic research. This expanding knowledge base emphasizes that sustainable herd development cannot be achieved through single-sector interventions; rather, it requires system-level thinking that accounts for the interconnectedness of biological, ecological, and economic factors. Furthermore, case study findings illustrate that breeder practices, institutional support, and local policy implementation critically affect reproductive performance, restocking capacity, and resilience against environmental and disease-related shocks.

Overall, the study's main contribution lies in establishing a unified analytical framework that captures the cross-cutting influences of policy, environment, and markets on cattle population stability. It demonstrates how vulnerabilities such as water scarcity, disease ecology, and price-driven culling intersect to shape herd dynamics, especially in regions with constrained movement and limited production buffers. By linking global scientific trends with locally grounded insights from Bali, the study advances the understanding of cattle population systems in developing contexts and provides evidence-based direction for more adaptive, sustainable management strategies.

Future research should deepen the integration of dynamic modeling, climate risk assessment, and genomic tools to fine-tune predictions of population trajectories under changing environmental and economic conditions. Additionally, exploring gender roles, smallholder decision-making, and value-chain modernization offers valuable pathways for strengthening herd resilience and improving equitable benefits across Indonesia's cattle sector. Through these directions, the field can continue building toward a more robust, data-driven foundation for sustainable beef cattle development.

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