Integrating Reproductive Technologies and Strategic Management for Sustainable Bali Cattle Population Growth in West Papua, Indonesia

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Abstract: Bali cattle are Indonesia's principal indigenous beef cattle resource and are especially important to smallholder livestock systems in eastern Indonesia. In West Papua, artificial insemination has become the main policy instrument for accelerating herd growth, but regional outcomes show that reproductive technology produces durable gains only when it is supported by effective management. This review integrates evidence on artificial insemination performance, semen handling, estrus detection, sexed semen, liquid semen, genomic and proteomic selection, and in vitro embryo production with the institutional and socio-economic conditions of Bali cattle farming in West Papua. Reported results from Manokwari indicate that conception can be high, whereas the gap between conception and calving remains a critical constraint. Comparative evidence from other Indonesian regions further shows that service accessibility, inseminator competence, deposition technique, parity, climate, nutrition, and farmer capability strongly influence reproductive outcomes. The review proposes an integrated management architecture built on six connected components: adaptive governance, reliable reproductive service delivery, farmer-centered extension, nutrition and animal health support, genetic resource stewardship, and performance-based data systems. Conventional artificial insemination should remain the operational core, while liquid semen, improved extenders, season-adjusted sexed semen, genomic and proteomic tools, and embryo technologies should be introduced according to local readiness rather than as stand-alone innovations. The central conclusion is that sustainable population growth depends not on maximizing insemination numbers, but on converting genetically sound inseminations into live, healthy, and reproductively valuable calves while maintaining the adaptive integrity of Bali cattle. This integrated approach provides a practical pathway for strengthening regional breeding programs in geographically dispersed tropical production systems.

Keywords: *Artificial Insemination, Bali Cattle, Genetic Resource Conservation, Reproductive Biotechnology, Strategic Livestock Management, West Papua.*

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I. INTRODUCTION

Indonesia's beef sector faces a persistent structural challenge: demand has expanded faster than the capacity of domestic production systems to supply slaughter cattle consistently. This imbalance has kept herd development and reproductive efficiency near the center of national livestock policy. Bali cattle, the domesticated descendant of the banteng, are strategically important within this agenda because they combine fertility, adaptation to tropical feed conditions, and suitability for smallholder management. Depending on the statistical base and year considered, the breed represents roughly one-quarter to one-third of the national cattle population and remains a major source of breeding stock and household assets in eastern Indonesia [1], [4]. Its importance is therefore biological, economic, and social: Bali cattle are both a national genetic resource and a practical production animal for farmers operating with limited land, capital, and external inputs.

West Papua provides a particularly important test of whether reproductive technology can be translated into sustainable regional herd growth. The province offers extensive land resources and a long history of cattle introduction through transmigration, government distribution, and smallholder development schemes. At the

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same time, settlements are dispersed, transport infrastructure is uneven, and many herds are managed under extensive or semi-extensive conditions. Farmers may observe animals only intermittently, breeding records are uncommon, and access to inseminators, liquid nitrogen, pregnancy diagnosis, and veterinary assistance varies sharply among districts. These characteristics make West Papua a high-potential but operationally difficult environment for reproductive intensification [4], [12].

Artificial insemination has been the principal technological response. National programs, including Upsus Siwab and its successor Sikomandan, have sought to increase the number of pregnant cows by expanding semen distribution, acceptor enrollment, inseminator services, and pregnancy monitoring. At national scale, these programs have been associated with positive cattle population growth and have been judged economically defensible when pregnancy and calf outputs are considered [10], [13]. In Manokwari, the reported conception rate indicates that artificial insemination is technically feasible under West Papuan conditions; however, the lower calving rate shows that successful fertilization does not automatically become a live calf [4]. The critical management question has consequently shifted from whether insemination can be performed to whether the whole reproductive pathway can be controlled from estrus detection to calf survival.

The available literature also shows that artificial insemination should no longer be treated as a single, uniform intervention. Outcomes vary with semen quality, thawing and deposition technique, timing relative to estrus, cow parity, nutritional condition, climate, sire-dam compatibility, and service accessibility [3], [5]-[8]. Emerging technologies could address some of these constraints. Antioxidant-enhanced extenders may protect sperm during cryopreservation [15]; liquid semen can reduce dependence on liquid nitrogen in selected service areas [16]; sexed semen can support targeted production of replacement females or market-preferred males [14]; and genomic, proteomic, and embryo technologies could improve the selection and multiplication of superior breeding animals [9], [17]-[21]. Yet these tools also require stronger laboratories, records, logistics, and human capability. Introducing advanced biotechnology into a weak service system can increase cost without improving calving output.

This review combines the technological and management perspectives that are often discussed separately. Its objectives are to synthesize evidence on the reproductive performance of Bali cattle under artificial insemination, assess the potential contribution and readiness of complementary reproductive technologies, identify the institutional and farm-level constraints that shape outcomes in West Papua, and propose an integrated management framework for sustainable population growth. The argument developed throughout the review is that population growth should be managed as a conversion chain: eligible cows must be detected in estrus, inseminated with viable and genetically appropriate semen, maintained through pregnancy, assisted at calving when necessary, and supported until the calf survives and enters the breeding or production population. Any weak link can erase the gains achieved by the preceding technology.

II. REVIEW SCOPE AND ANALYTICAL APPROACH

This paper is an integrative narrative review based on the two supplied review manuscripts and the scientific and institutional sources cited within them. The evidence base covers five connected domains: the origin and conservation genetics of Bali cattle; reproductive performance under artificial and natural breeding; national and regional artificial insemination programs; innovations in semen processing, sexing, fertility evaluation, and embryo production; and management conditions in Indonesian smallholder cattle systems. The review does not claim the exhaustive coverage of a systematic review. Instead, it reorganizes the available evidence around a decision-oriented question: which combination of technology and management is most likely to produce sustainable population growth in West Papua?

Three analytical principles guide the synthesis. First, reproductive indicators are interpreted as a sequence rather than as isolated values. Service per conception measures the number of inseminations required for a confirmed conception, conception rate measures early reproductive success, and calving rate measures the proportion that ultimately produces calves. Differences among these indicators reveal where losses occur. Second, technical results are interpreted in their production context. A conception rate obtained in a breeding center cannot be transferred directly to a remote grazing system without accounting for estrus observation, travel time, nutrition, and follow-up. Third, sustainability includes genetic integrity and adaptive capacity, not only numerical growth. Artificial insemination can disseminate superior genes rapidly, but overuse of a narrow sire group can also reduce diversity and increase relatedness [1], [9], [11].

The resulting framework therefore evaluates technologies along four dimensions: biological effectiveness, logistical fit, institutional requirements, and genetic consequences. Evidence from West Papua receives priority, while studies from other Indonesian regions are used as comparative evidence where local data remain limited. Because study designs, years, breeds of semen, and farm systems differ, numerical results are presented as indicative rather than directly pooled. This approach avoids false precision while still allowing consistent patterns and management implications to be identified.

III. BALI CATTLE AND THE WEST PAPUA PRODUCTION SYSTEM

➤ *Biological and Genetic Importance*

Bali cattle occupy a unique position among Indonesian livestock breeds. Genetic and historical evidence identifies them as the domesticated form of banteng rather than a

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conventional zebu-derived breed [4], [11]. This origin underlies traits that farmers value, including adaptation to tropical environments, reproductive fitness under low-input conditions, and the ability to use fibrous feed resources. It also gives the breed conservation importance beyond immediate beef production. A breeding program that increases numbers while eroding the characteristic genetic identity of Bali cattle would therefore achieve only a partial and potentially temporary form of success.

Genomic studies indicate that Bali cattle have experienced historical bottlenecks and that effective population size requires active monitoring [9]. This does not imply that the breed is incapable of improvement; rather, it means that selection intensity and the distribution of sire contributions must be managed carefully. Artificial insemination magnifies this issue because one bull can generate thousands of offspring across many districts. The technology can rapidly raise genetic merit when sires are well evaluated, but it can just as rapidly spread undesirable traits or concentrate ancestry when semen procurement is based mainly on availability. Conservation-oriented breeding soundness evaluation and cryobanking have consequently been recommended as integral components of Bali cattle development [1].

The genetic objective should also be defined locally. For West Papua, maximum mature size is not necessarily the optimal breeding goal. Cows must remain fertile under seasonal feed variation, walk or graze in extensive systems, and calve safely without intensive supervision. Growth traits are economically important, and genome-wide association work has begun to identify genomic regions related to birth weight [19]. However, increasing birth weight without considering dam size and calving ease can increase dystocia. A balanced index should therefore include fertility, calving ease, calf survival, growth, structural soundness, and adaptation. The key strategic principle is to improve performance without replacing the biological qualities that make Bali cattle suitable for the region.

➢ *Smallholder Management and Service Environment*

West Papuan cattle production is dominated by smallholders operating with limited formal recording and variable access to inputs. Traditional systems described in the region commonly involve free or semi-controlled grazing, low use of formulated feed, and limited routine reproductive observation [12]. Herd ownership can also be distributed through government or private profit-sharing arrangements. Such schemes may expand access to cattle, but reproductive outcomes depend on the technical accompaniment provided to caretakers. Distribution of animals without sustained breeding guidance can increase head numbers temporarily while leaving conception, calving, and mortality constraints unresolved.

Extensive management affects nearly every stage of artificial insemination. Estrus may begin while cows are away from the household, so the first visible signs can be missed. The farmer must then contact an inseminator, who may travel a long distance with semen and equipment. If reporting or travel is delayed, insemination occurs outside the optimal fertility window. Pregnancy diagnosis may not be performed, repeat breeders may remain unidentified, and late-gestation cows may not receive additional feed or closer observation. These are not minor implementation details; they determine whether a semen straw becomes a calf.

The geography of the province further complicates standardized service design. Lowland transmigration areas with road access can support scheduled routes and relatively dense acceptor groups, whereas highland, island, or remote settlements may require mobile service points, local para-technicians, or alternative semen preservation strategies. Comparative evidence from Polewali Mandar shows that less accessible highland systems can have higher service-per-conception values and lower calving rates than lowland systems served under the same broad program [3]. The implication for West Papua is that a province-wide numerical target should be disaggregated by service ecology. A delivery model appropriate for peri-urban Manokwari should not be assumed to work in every district.

Farmer incentives also matter. Smallholders may prefer natural mating when a bull is locally available because it imposes less coordination cost, even if genetic control is weaker. They may sell superior females to meet immediate cash needs, undermining the future breeding base. Conversely, farmers are more likely to report estrus and protect pregnant cows when the expected value of the calf is visible and when service providers respond reliably. Sustainable reproductive programs therefore require a credible exchange: farmers contribute observation, handling, and follow-up, while institutions provide timely service, transparent breeding information, and support when pregnancy or calving problems occur.

IV. ARTIFICIAL INSEMINATION PERFORMANCE AND ITS DETERMINANTS

➢ *Regional Performance and Interpretation*

Artificial insemination remains the most mature reproductive technology available for large-scale Bali cattle development. The Manokwari evaluation under Upsus Siwab reported a service per conception of 2.3, a conception rate of 85.91 percent, and a calving rate of 78.57 percent among 560 acceptor cows [4]. These values demonstrate that conception can be achieved at a high rate in the region. At the same time, the difference between conception and calving identifies pregnancy maintenance and calving management as important loss points. A program evaluated only by insemination count or early pregnancy would overestimate its contribution to population growth.

Comparative results reinforce this interpretation. In Polewali Mandar, lowland herds achieved service-per-conception values of approximately 1.17 to 1.26 and a reported calving rate of 75.7 percent, whereas highland groups showed service-per-conception values of about 1.30 to 1.50 and calving rates around 50.0 to 61.0 percent [3]. The differences were linked to accessibility, insemination timing, and semen or sire choices. Studies of Bali cattle

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under different management systems likewise show that reproductive performance is conditional on husbandry and breeding strategy rather than an invariant breed characteristic [8]. Table I summarizes selected indicators, but the figures should not be ranked mechanically because populations, protocols, and outcome definitions differ.

Historical breeding-center data provide a broader biological reference. Gunawan and colleagues reported an average pregnancy rate of 88.4 percent, age at first calving of approximately 43.9 months, calving interval near 360.9 days, and preweaning mortality around 7.6 percent, with parity and year affecting performance [6]. Farmer-level work also confirms parity-related variation in service per conception, days open, and other reproductive indicators [7]. These findings matter for program design because acceptor cows are not biologically equivalent. Recording parity, postpartum interval, body condition, and reproductive history would allow services to distinguish healthy first-service candidates from cows requiring nutritional, clinical, or management intervention.

➢ *Semen Quality, Handling and Deposition*

The biological quality of semen at insemination is the foundation of artificial insemination success. Frozen semen is produced under controlled conditions, but field fertility depends on storage temperature, handling frequency, thawing procedure, and the interval between preparation and deposition. A genetically superior straw that has been repeatedly lifted above the frost line of a nitrogen tank or thawed inconsistently may have little practical value. In West Papua, where nitrogen supply and transport routes may be irregular, cold-chain management should be audited as a continuous process rather than assumed from the presence of storage containers.

Insemination technique is equally important. A comparative trial in Bali cattle found that conception outcomes differed according to the site of semen deposition, with deposition closer to the expected fertilization pathway producing better results than less appropriate placement [5]. The study highlights why inseminator certification cannot be treated as a one-time qualification. Competence should be maintained through refresher practice, field supervision, and periodic evaluation using outcome data. Service-per-conception values linked to individual inseminators can identify training needs, but they must be adjusted for cow condition, location, and case difficulty to avoid unfair comparisons.

Bull selection and sire-dam matching are also part of technical execution. Using large-framed exotic semen on small Bali cows may increase expected calf growth but can also increase calving difficulty when birth size exceeds maternal capacity. The Manokwari evidence associates part of the conception-to-calving loss with dystocia and management after conception [4]. A regionally appropriate semen portfolio should therefore distinguish pure Bali breeding, carefully planned crossbreeding, and terminal production objectives. Farmers need to know whether resulting female calves are suitable as replacements or should not be returned to the breeding nucleus.

➢ *Estrus Detection, Timing and Farmer Participation*

Estrus detection is the main point at which farmer behavior and reproductive biology intersect. Artificial insemination operates within a limited period around ovulation, and delayed recognition reduces the probability that viable sperm and oocytes will meet at the correct time. In extensive systems, signs such as restlessness, mounting behavior, vulvar changes, and mucus discharge may be unnoticed or interpreted late. The inseminator then receives an incomplete estimate of estrus onset. Comparative field evidence links better farmer understanding and faster service access with improved reproductive outcomes [3], [5].

Extension should therefore move beyond general awareness sessions. Farmers need practical observation routines, visual examples of primary and secondary estrus signs, a simple method for recording the first observed sign, and a reliable communication channel to the service provider. Group-based systems can assign an estrus monitor or coordinator, reducing the burden on individual households and allowing several cows to be scheduled in one route. Mobile messaging can improve coordination where coverage is available, but technology is useful only when the service responds predictably. Repeated failure to receive timely service weakens farmer motivation to report future events.

Synchronization can reduce dependence on spontaneous detection in selected clusters, but it should not be applied indiscriminately. Hormonal protocols require accurate animal identification, appropriate body condition, trained personnel, and scheduled insemination capacity. They are most suitable where enough eligible cows can be assembled and followed. In very dispersed herds, improving basic observation and response time may yield a larger return than introducing a protocol that is difficult to complete.

➢ *From Conception to a Surviving Calf*

High conception rates can create a false sense of completion. Sustainable population growth depends on pregnancy retention, safe parturition, neonatal survival, and the later retention of selected replacement animals. The Manokwari gap between conception and calving suggests that the post-insemination period deserves as much management attention as semen delivery [4]. Pregnancy diagnosis should be scheduled rather than optional, enabling nonpregnant cows to be re-enrolled and pregnant cows to enter an appropriate management pathway.

Late-gestation support is particularly important under seasonal feed limitation. Cows need sufficient energy, protein, minerals, water, and freedom from severe disease or stress to maintain pregnancy and prepare for lactation. The program should identify high-risk pregnancies, including small dams carrying calves from larger sires, cows with poor body condition, and animals with previous calving problems. A simple referral and emergency contact system

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can prevent avoidable losses. After calving, recording calf sex, birth date, dam, sire code, assistance required, and survival at defined ages would convert field events into information for future breeding decisions.

This broader endpoint changes program incentives. When agencies are rewarded mainly for straws distributed or pregnancies diagnosed, resources concentrate at the front of the chain. When performance is assessed by live calves, calf survival, and retained breeding females, attention shifts toward nutrition, calving services, health, and records. The latter indicators better represent actual population growth and should become the principal measures of program effectiveness.

V. COMPLEMENTARY REPRODUCTIVE TECHNOLOGIES

➢ *Extenders, Cryoprotection and Liquid Semen*

Improving semen preservation can increase the reliability of artificial insemination without changing the basic service model. Cryopreservation exposes sperm cells to thermal, osmotic, and oxidative stress. In Bali bull semen, the addition of green tea extract to a Tris-based egg-yolk extender improved post-thaw motility, viability, and plasma membrane integrity under experimental conditions [15]. Such antioxidant strategies are promising because they could reduce fertility loss during freezing and thawing. Nevertheless, laboratory improvement should be validated through field conception and calving outcomes before adoption at scale. A statistically better motility value is valuable only if it produces more viable pregnancies under service conditions.

Liquid semen offers a different logistical strategy. Trials in Bali cattle show that chilled semen prepared with suitable diluents can achieve useful non-return and conception results when insemination occurs within the required storage period [16]. For West Papua, liquid semen may reduce dependence on continuous liquid nitrogen in areas located near a collection or processing point. It is not a universal replacement for frozen semen because its usable life is shorter and transport must be tightly scheduled. The most realistic approach is a differentiated network: frozen semen for long-distance storage and routine district services, and liquid semen for organized breeding zones where collection, processing, and same-day or short-interval delivery are feasible.

Both innovations illustrate a general rule. A technology should be selected according to the dominant bottleneck. Where semen damage during freezing is the problem, improved extenders may help. Where nitrogen supply is unreliable but road travel from a semen center is predictable, liquid semen may be advantageous. Where neither transport nor coordination is reliable, local service infrastructure must be strengthened before changing the semen formulation.

➢ *Sexed Semen and Planned Calf-Sex Outcomes*

Sexed semen can align calf production with breeding objectives. Female-biased semen can accelerate the supply of replacement heifers, while male-biased semen may support beef-market preferences. A study in South Papua found that conventional semen generally produced stronger fertilization outcomes, but increasing the dose of sexed semen improved results under the hotter season, indicating that climate and dose interact [14]. This evidence argues against transferring a single sexed-semen protocol across seasons and locations.

The economic value of sexed semen also depends on the herd objective and accuracy of management. Its lower sperm concentration and greater processing stress can make timing and insemination technique more demanding. It should first be used in well-managed cows with known reproductive histories, good body condition, and reliable estrus detection. In a nucleus or multiplier herd, female-biased semen could expand genetically valuable dam lines. In commercial terminal-cross systems, male-biased semen may be preferred. Without a defined breeding structure, however, sexed semen can become an expensive novelty rather than a strategic tool.

➢ *Genomic and Proteomic Selection*

Genomic information can strengthen the management of both improvement and diversity. Linkage disequilibrium and effective population size analyses provide a basis for monitoring genetic structure in Bali cattle [9], while association studies can identify genomic regions related to economically important traits such as birth weight [19]. For West Papua, the immediate application is not necessarily full genomic selection of every animal. A more feasible starting point is genotyping AI sires, nucleus females, and a representative sample of district populations to monitor relatedness, verify parentage, and prevent excessive use of closely related bulls.

Proteomic evaluation offers a complementary route for improving sire selection. Analysis of Bali-polled bull seminal plasma has identified proteins associated with sperm function and field reproductive indicators [17]. These biomarkers may eventually help distinguish bulls whose conventional semen measurements appear acceptable but whose fertility differs. Proteomic tools remain research-intensive and should not replace standard breeding soundness examinations. Their value lies in adding biological resolution to decisions about which bulls should enter large-scale semen production.

Together, genomic and proteomic tools could make artificial insemination more precise. Genomics addresses ancestry, diversity, and trait potential; proteomics can contribute information about semen function and fertility. Their strategic benefit will be realized only when laboratory results are linked to field records. A sire cannot be evaluated adequately if conception, calving ease, calf survival, and growth are not traced back to its semen code.

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➢ *In Vitro Embryo Production and Embryo Transfer*

In vitro embryo production offers the possibility of multiplying superior maternal as well as paternal genetics. Indonesian research has shown that Bali cattle oocytes fertilized with semen from bulls classified by sperm motility can develop to cleavage and blastocyst stages, supporting the use of embryo systems for fertility assessment and future genetic multiplication [18]. Internationally, advances in oocyte maturation, fertilization, embryo culture, sex selection, and recipient management have expanded the commercial potential of bovine embryo production [20], [21].

For West Papua, embryo technology is a medium- to long-term option rather than an immediate substitute for artificial insemination. It requires donor and recipient selection, synchronization, laboratory quality control, skilled transfer, and intensive follow-up. The cost per calf is also substantially higher than routine insemination. A realistic role would be the production of a limited number of high-value breeding animals in a nucleus herd, followed by wider dissemination through semen and selected natural-mating bulls. This tiered model captures the multiplication advantage of embryo technology while keeping field service economically manageable.

Embryo programs must also address biological risks, including variation in embryo competence, recipient failure, and possible developmental effects associated with culture conditions [20], [21]. Introduction should therefore be staged through research partnerships and transparent performance evaluation. The existence of a sophisticated laboratory does not by itself justify field expansion; the technology should demonstrate that it can produce healthy, fertile offspring and contribute to the defined regional breeding objective.

VI. AN INTEGRATED STATEGIC MANAGEMENT FRAMEWORK

➢ *Adaptive Governance and Locally Differentiated Targets*

National reproductive programs provide essential funding, standards, and coordination, but Indonesia's cattle development experience shows that uniform input targets do not consistently produce uniform outcomes across heterogeneous regions [2]. West Papua needs a nested governance model in which national institutions secure semen quality, genetic standards, and financing; provincial authorities coordinate breeding objectives and logistics; districts organize service delivery; and farmer groups manage observation, animal assembly, and local records. Each level should have explicit responsibilities and indicators.

Targets should be defined around outcomes and adjusted to service conditions. Accessible lowland clusters may be expected to achieve shorter response times and lower service-per-conception values. Remote areas may initially be assessed on service coverage, timely reporting, and reduction of missed estrus, followed by progressive improvement in pregnancy and calving. This is not a relaxation of standards; it is a sequence that recognizes different starting points. Comparing districts only by the number of straws used can reward inefficient repeat insemination and conceal post-conception losses.

Governance must also protect breeding direction. Semen procurement should follow a published plan specifying the role of pure Bali semen, the conditions under which crossbreeding is allowed, and the intended use of male and female offspring. Bull identity, genetic evaluation, and distribution volume should be traceable. A district should know not only how many straws it received, but from which sires, for which cow populations, and with what cumulative genetic contribution.

➢ *Reliable Service and Cold-Chain Logistics*

Service reliability is the operational bridge between farmer observation and biological success. The province should map cattle density, road access, travel time, nitrogen supply points, and inseminator locations, then design routes and service zones around actual demand. Mobile tanks and scheduled replenishment can support remote routes, while strategically located mini-depots can reduce the distance between storage and farms. Inventory systems should flag low nitrogen levels, expiring supplies, and uneven straw distribution before service interruption occurs.

Inseminator deployment should combine geographic coverage with workload quality. Too few technicians create delay; too many without enough cases can reduce proficiency and raise cost. A hub-and-spoke arrangement can place experienced inseminators at district hubs and trained local personnel in satellite communities, with referral for difficult cases. Digital or paper-based dispatch logs should record the time of estrus report, arrival, insemination, semen code, and follow-up. These data make response time measurable and allow managers to distinguish a biological fertility problem from a logistical timing problem.

Quality assurance should include regular tank inspection, thawing checks, hygiene, deposition technique assessment, and review of reproductive outcomes. The goal is not punitive ranking but continuous improvement. When one route shows unusually high service-per-conception values, the investigation should consider semen handling, inseminator technique, farmer timing, cow selection, and environmental conditions together.

➢ *Faremer-Centerd Extension and Shared Responsibility*

Farmer training is most effective when it is connected to the exact decisions farmers must make. Core modules should include identifying estrus, recording onset time, safely restraining cows, maintaining body condition, recognizing warning signs during pregnancy and calving, and reporting births and losses. Demonstration with live animals or clear visual media is preferable to lecture-only extension. Training should be repeated across seasons because observation conditions and nutritional risks change.

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Farmer groups can become active service partners. A group reproductive calendar can identify postpartum cows, expected estrus periods, pregnancy-check dates, and anticipated calving. One trained member can coordinate communication with the inseminator, while the group can organize temporary gathering facilities for cows. This arrangement lowers travel and transaction costs and makes synchronization or scheduled pregnancy diagnosis more feasible. It also creates peer accountability for records and follow-up.

Participation depends on trust and perceived benefit. Service providers should communicate semen type, expected calf characteristics, and realistic success probabilities. When an insemination fails, the response should focus on diagnosis rather than blame. When a high-risk pregnancy is identified, the farmer should know where assistance is available. A transparent, responsive system strengthens willingness to adopt both conventional and emerging technologies.

- *Nutrition, Climate Resilience and Animal Health*

Reproductive technologies cannot compensate for severe nutritional deficiency. Body condition affects estrus expression, conception, pregnancy maintenance, and postpartum recovery. District programs should align insemination campaigns with forage availability and promote feed reserves for late gestation and the early postpartum period. Locally available crop residues, planted forages, and mineral supplementation can be incorporated according to agro-ecological zone. The objective is not to create a high-cost feeding system but to prevent predictable seasonal deficits at biologically critical stages.

Climate also modifies reproductive performance. The South Papua sexed-semen study demonstrated seasonal differences associated with heat conditions and showed that semen protocol may require adjustment [14]. More broadly, service schedules should reduce animal handling during peak heat, ensure access to water and shade, and avoid interpreting heat-related changes in estrus behavior as simple farmer failure. Climate information can be incorporated into breeding calendars and semen allocation decisions.

Animal health support should be integrated with reproductive visits. Inseminators and extension personnel can screen for poor body condition, abnormal discharge, lameness, or signs requiring veterinary referral. Vaccination and parasite-control strategies remain the responsibility of competent animal-health authorities, but reproductive programs should not operate as isolated vertical services. A cow affected by disease may consume semen and staff time repeatedly without a reasonable chance of pregnancy or calf survival. Basic eligibility screening protects both animal welfare and program efficiency.

- *Genetic Stewardship and a Structured Breeding System*

A sustainable breeding structure should separate nucleus, multiplier, and commercial functions. The nucleus maintains the highest level of pedigree, performance, and genetic monitoring and can use genomic or embryo technologies selectively. Multiplier herds expand evaluated Bali genetics through artificial insemination and controlled natural mating. Commercial herds use semen according to defined purebreeding or terminal-cross objectives. This structure prevents advanced technologies from being spread without purpose and creates a pathway from research to field production.

Sire use should be monitored to prevent excessive genetic concentration. District semen allocations can rotate unrelated or less-related sires, and genomic checks can be introduced where pedigree is incomplete. Superior local bulls remain important in communities where artificial insemination access is intermittent. They should undergo breeding soundness evaluation and be managed as part of the same genetic plan rather than treated as uncontrolled competitors to artificial insemination [1]. Cryobanking semen and, where feasible, embryos from well-characterized animals provides insurance against future loss of diversity.

Female selection is equally important. Population programs often focus on semen because it is a visible technological input, but long-term progress depends on which heifers are retained. Farmers should be encouraged to keep healthy daughters from proven dams and appropriate sires, while culling decisions should consider reproductive failure, structural problems, and genetic objectives. Incentives or credit mechanisms may be needed to reduce the sale of superior young females for immediate cash

- *Data Systems and Performance-Based Learning*

The integrated framework requires a minimum data set that can be collected reliably in field conditions. Essential records include animal identificationData, location, breed or cross, parity, body condition, estrus report time, insemination time, semen and sire code, inseminator, pregnancy diagnosis, calving outcome, assistance, calf sex, and survival. Additional genomic or laboratory data should be linked only where animal identification is secure. A small complete data set is more valuable than a complex form that is rarely finished.

Performance dashboards should report the full reproductive conversion chain: eligible cows, cows inseminated, cows pregnant, cows calved, live calves at birth, calves surviving to weaning, and replacement females retained. Service per conception and response time can diagnose efficiency, while conception-to-calving loss identifies pregnancy and parturition problems. Results should be reviewed by district teams with farmer representatives, creating a feedback loop in which evidence changes training, routes, semen choices, and support services.

Data quality must be protected through simple definitions and periodic verification. For example, conception rate should specify the denominator and timing of pregnancy diagnosis; calving rate should state whether it is calculated from inseminated or confirmed-pregnant cows. Consistent definitions allow comparisons across years and

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prevent apparent improvement caused by changing measurement. Figure 1 summarizes how technology, management pillars, and outcome indicators interact.

VII. PHASED IMPLEMENTATION ROADMAP FOR WEST PAPUA

Implementation should proceed in phases because districts differ in readiness and because advanced technologies depend on reliable basic services. In the first phase, the province should consolidate artificial insemination quality. Priority actions include mapping service zones, auditing the cold chain, refreshing inseminator skills, standardizing cow eligibility, strengthening estrus reporting, and ensuring pregnancy and calving follow-up. Existing data from Manokwari suggest that the largest immediate gain may come from reducing the loss between conception and calving rather than simply increasing the number of first inseminations [4].

The second phase should introduce context-specific innovations. Antioxidant-enhanced semen processing can be evaluated through controlled field trials; liquid semen can be tested in organized zones close enough to a production center for timely delivery; and sexed semen can be allocated to selected cows in nucleus or multiplier herds with season-specific protocols [14]-[16]. Each pilot should define a comparator, record cost per live calf, and include animal welfare and genetic outcomes. Technologies that improve laboratory measures but do not improve live-calf output should not be scaled automatically.

The third phase should establish precision breeding capacity. Genotyping of major AI sires and nucleus females, parentage verification, and monitoring of sire contribution can create the foundation for regional genetic stewardship [9], [19]. Proteomic fertility markers may later complement conventional semen evaluation [17]. Embryo production and transfer should be concentrated in a limited nucleus program linked to universities, breeding centers, and competent veterinary services [18], [20], [21]. Offspring from this program can then contribute through semen, selected bulls, and replacement females.

Across all phases, financing should follow verified outputs. Budgets must cover nitrogen, transport, records, pregnancy diagnosis, extension, and calving support rather than semen alone. Public investment is justified where genetic improvement and service access create benefits beyond individual farms, but cost-sharing can be introduced for premium technologies once farmers perceive clear value. The national economic evaluation of mass artificial insemination supports continued investment, while also underscoring the need to connect expenditure with measurable reproductive and economic returns [13].

A practical pilot design would select three contrasting service zones: an accessible lowland cluster, an intermediate rural corridor, and a remote or difficult-access cluster. The same minimum indicators would be collected in each, but the delivery model would differ. Such a design would produce locally useful evidence on route density, response time, semen system, farmer coordination, and cost per surviving calf. It would also prevent the province from scaling a model validated only in the most accessible communities.

Table 1 Selected Reproductive Performance Indicators for Bali Cattle Under Artificial Insemination.

Location or Study Context	S/C	Conception or Pregnancy	Calving or Related Outcome	Interpretive Note
Polewali Mandar lowland, West Sulawesi [3]	1.17-1.26	Not consistently reported	75.7% calving rate	Accessible service area; lower repeat-service burden
Polewali Mandar highland, West Sulawesi [3]	1.30-1.50	66.7-77.0% CR	50.0-61.0% calving rate	Accessibility and timing constraints reduced outcomes
Manokwari, West Papua, Upsus Siwab [4]	2.30	85.91% CR	78.57% calving rate	Strong conception; post-conception losses remain important
Bulukumba deposition trial [5]	Site dependent	Highest at deposition site closest to target pathway	Not reported	Technique and semen placement affected conception
Bali cattle breeding-center data [6]	Not stated	88.4% pregnancy rate	43.9 mo first calving; 360.9 d calving interval; 7.6% preweaning mortality	Parity and year significantly influenced performance

Note: S/C = Services Per Conception; CR = Conception Rate. Values are Indicative because Study Designs, Populations, and Denominators Differ.

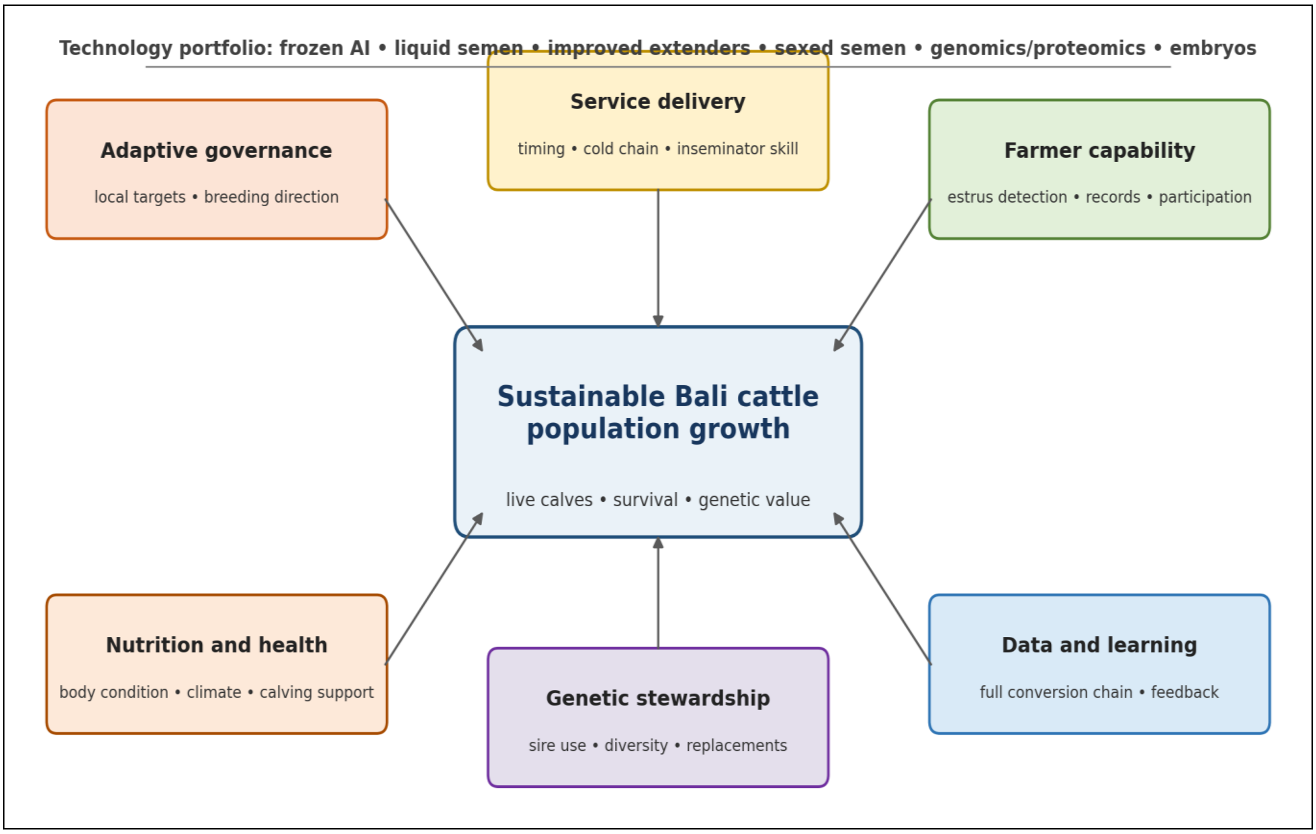

Fig 1 Integrated Technology-Management Architecture for Sustainable Bali Cattle Population Growth in West Papua.

Table 2 Readiness and Management Requirements for Reproductive Technologies and Supporting Interventions.

Technology or Management Option	Primary Contribution	Main Constraint	Priority Requirement for West Papua	Readiness
Conventional frozen-semen AI [3]-[5]	Rapid dissemination of selected sires; broad field applicability	Estrus timing, cold chain, technician access, post-conception loss	Strengthen routes, quality assurance, pregnancy and calving follow-up	Immediate core
Improved extenders [15]	Protect post-thaw sperm quality	Field fertility and cost-effectiveness need validation	Controlled field trials linked to live-calf outcomes	Near term
Liquid semen [16]	Reduces dependence on liquid nitrogen in selected service zones	Short storage life and strict delivery schedule	Use near processing hubs with reliable same-day logistics	Targeted near term
Sexed semen [14]	Supports planned replacement-female or male-calf production	Lower fertility, higher cost, seasonal sensitivity	Use in selected cows with accurate timing and season-adjusted protocols	Targeted pilot
Genomic and proteomic tools [9], [17], [19]	Improve sire selection, parentage control, diversity monitoring, fertility prediction	Laboratory cost, data linkage, limited field records	Start with AI sires, nucleus females, and representative population samples	Medium term
In vitro embryo production [18], [20], [21]	Multiplies elite maternal and paternal genetics	High technical, recipient, and cost requirements	Concentrate in a nucleus program linked to research institutions	Long term
Farmer-group reproductive management [3], [12]	Improves estrus detection, scheduling, records, and follow-up	Requires trust, repeated training, and responsive services	Make extension and group coordination a funded program component	Immediate core

VIII. RESEARCH PRIORITIES AND LIMITATIONS

The literature reveals several research priorities. First, West Papua needs longitudinal studies that follow cows from insemination through weaning. Most program evaluations emphasize conception and calving, leaving limited information on embryonic loss, causes of dystocia, neonatal mortality, and retention of replacement females. Second, field trials should compare semen systems and sire types under clearly defined management and seasonal conditions. Random or matched designs would help separate technological effects from differences in cow quality and service access.

Third, the genetic consequences of current semen distribution should be measured. Genotyping can estimate relatedness, effective population size, and the contribution of heavily used sires, while field records can reveal whether genetic improvement is accompanied by calving difficulty or loss of adaptation [9], [19]. Fourth, economic analyses should calculate cost per pregnancy, live birth, weaned calf, and retained breeding female. These endpoints would show whether advanced technologies create value under smallholder conditions, not only whether they work biologically.

Fifth, implementation research should evaluate extension and logistics as interventions. For example, farmer-group estrus monitoring, mobile dispatch, local nitrogen depots, or scheduled pregnancy diagnosis can be compared using response time and live-calf outcomes. Such studies would elevate management from background context to a testable component of reproductive performance.

This review has limitations. It is based on the two supplied manuscripts and their cited literature rather than an independently conducted systematic search. Direct West Papuan evidence remains concentrated in a small number of locations and program periods, and several emerging technologies have been evaluated mainly under experimental or non-West-Papuan conditions. Numerical comparisons are therefore descriptive. Nevertheless, the consistency of findings across reproductive biology, regional field studies, and management research supports the central conclusion that technology and service systems must be designed together.

IX. CONCLUSION

Bali cattle population growth in West Papua cannot be secured by increasing artificial insemination coverage alone. Artificial insemination is technically feasible and should remain the operational core of the regional breeding program, but its value depends on timely estrus detection, viable semen, skilled deposition, appropriate sire choice, pregnancy maintenance, safe calving, calf survival, and retention of genetically valuable animals. The gap between conception and calving in Manokwari is a practical reminder that early reproductive success is not equivalent to population growth [4].

Complementary technologies can strengthen this system when introduced according to need and readiness. Improved extenders may protect sperm quality, liquid semen may serve selected routes with weak nitrogen access, sexed semen may accelerate planned male or female production, and genomic, proteomic, and embryo tools may increase selection accuracy and multiplication of superior animals [9], [14]-[21]. None of these options removes the need for farmers, inseminators, veterinarians, breeding institutions, and government agencies to coordinate their actions.

The proposed framework places six elements within one management architecture: adaptive governance, reliable service logistics, farmer-centered extension, nutrition and animal health support, genetic stewardship, and performance-based data. Its success should be judged by the conversion of eligible cows into live and surviving calves, the efficiency and equity of service delivery, and the preservation of Bali cattle's adaptive genetic identity. By managing the entire reproductive pathway rather than a single technological event, West Papua can transform reproductive biotechnology from an input-distribution program into a sustainable regional breeding system.

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