Effect of Rearing of Calves (Cow vs Artificial) on the Dam's Milk Production

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Himal Dhanushe

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Abstract

New Zealand has a unique dairy production system characterised by pasture-based feeding and highly seasonal calving, with most calves born in spring and artificially reared. However, rearing calves on cows is an alternative to improve the growth rate of calves. Little research has compared artificial and dam-suckling rearing, and its influence on milk yield and composition in lactating dairy cows remains unclear. Therefore, this study aimed to assess the effect of cow-rearing of calves on dams' milk production over an entire lactation period in a seasonal pasture-based, once-a-day milking herd in New Zealand.

Thirty-nine cows (Jersey, Holstein-Friesian, and their crossbreeds) were assigned to either natural suckling (Cow, n = 20) or artificial rearing (Shed, n = 19) groups at calving. Cows in the Shed group had their calves removed within 36 hours of birth and had no contact with dams thereafter. Dams in the Cow group remained with their calves at all times except during milking, until weaning at a mean of 68 ± 15 days, reduced over three days. All cows were managed as a group on pasture and were milked once-a-day for their entire lactation. Daily meter milk data were collected until December, and monthly herd-test records were obtained throughout the season.

During the pre-weaning phase, the Cow group recorded 489 kg lower milk yield, 33 kg less fat, 23 kg less protein, and 56 kg less milksolids than the Shed group ($p < 0.0001$). These differences correspond to the expected milk intake of calves (6–8 litres/day) directly from their dams under unrestricted suckling. Milk fat concentration differed between pre- and post-weaning phases, and a significant Treatment x Phase interaction indicated a greater increase in fat concentration following weaning in cows rearing calves, while no within-phase treatment differences were observed. Cumulative milk yield, component yields, and concentrations were not significantly different between treatments post-weaning. Total lactation yields of milk, fat, protein, and milksolids were also not statistically different between groups. The Cow group exhibited a slightly later peak and greater lactation-curve persistency, although this did not translate into differences in overall season production.

Extended cow–calf contact reduced saleable milk yield only during the pre-weaning period, reflecting milk diverted to calf growth rather than an actual drop in production and did not compromise overall lactation performance in this OAD, pasture-based system. Further research should quantify the actual milk suckled by calves, the long-term effects on udder health, reproductive performance, and whole-season milksolids output across successive lactations, and assess calf growth and other on-farm implications to evaluate the potential benefits and trade-offs of rearing strategies within commercial pasture-based dairy systems.

Keywords: calf rearing, pasture-based, milk composition, lactation period, dam rearing, cow-calf contact.

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1. Introduction

Dairy farming plays a crucial role in global agriculture by producing milk and its associated by-products, thereby contributing to the supply of essential nutrients for human consumption (Shamsuddoha et al., 2023). In New Zealand, the dairy sector accounts for about 35% of total exports and over 25% of foreign earnings from goods and services, employs about 55,000 people, and puts $3.6 billion directly into the pockets of employees (Lee, 2023). Overall, it represents 2.2 % of the national GDP from dairy farming, with an additional 1% from dairy processing (DairyNZ, 2023b).

New Zealand has a unique dairy production system characterised by pasture-based feeding and highly seasonal calving. The pasture-based dairy production system in New Zealand is considered a low-input and cost-effective system, which makes it different from others, which primarily rely on either grains or concentrates (Stafford, 2017). Furthermore, farmers' income is based on milksolids rather than milk volume, emphasising the importance of milk composition in securing profitability (Bryant et al., 2024).

Milk production in dairy cows is a complex biological process that begins very shortly after calving, when the mammary gland initiates milk secretion (Neville et al., 2001) and is composed of several nutritional components, including protein, fat, vitamins, minerals, and water (Geary et al., 2010). The pattern of milk production over time is described by the lactation curve and is influenced by seasonal pasture growth, parity, breed, and farm management practices such as milking frequency and calf-rearing systems (Jiang et al., 2020). The lactation curve often shows a rapid increase in milk yield after calving, with the peak occurring 6-8 weeks after calving. After that, the lactation curve gradually declines until dry off (Gengler, 1996). In pasture-based dairy systems, the spring season calving allows peak feed requirements to align with the period of maximal pasture availability, effectively fulfilling the nutritional demands of early lactation cows from grazed pasture (Timlin et al., 2021).

Given the seasonal calving, approximately 4.6 million calves are born between July and September each year in New Zealand (DairyNZ, 2020), with only about one-quarter reared as replacement heifers, and the remaining either slaughtered as bobby calves, raised for meat, reared as sires for reproduction, or killed on farm (Mellor, 2012). Well-managed rearing practices can convert calves into healthy, high-performing animals, which is key to farm productivity and profitability (Verdon & Tilbrook, 2021). However, challenges such as diseases, poor colostrum intake, exposure to environmental stressors, and poor housing conditions can increase the calf morbidity and mortality rate, decreasing the overall farm productivity and profitability (Heinemann et al., 2021). Farm management practices and technological advancements such as automated feeding systems, precision nutrition, and real-time health monitoring can significantly improve rearing efficiency, reduce labour costs, and improve overall calves' health (Costa et al., 2016). Rearing calves on cows is also an alternative to improve the growth rate of calves (Bryant et al., 2024; Mac et al., 2022) and potentially reduce labour costs (Martín et al., 2023). However, it is not well-known what effect calf suckling has on the maternal lactation curve and milk composition.

Little research within New Zealand’s pasture-based systems has compared artificial and dam-suckling rearing. Understanding the relationship between calf rearing methods and overall lactation is crucial for dairy production efficiency, as changes in the total volume or timing of saleable milk have a direct impact on farm income. Therefore, the objective of this project was to explore how two calf-rearing systems, natural (dam-suckling) versus artificial (hand-rearing or teat feeding), influence the dam’s milk production during the whole lactation.

2. Review of Literature

This literature review will consider the physiological basis of milk production, including mammogenesis, lactogenesis, milk ejection, and involution, as well as external factors such as nutrition, parity, and milking frequency. Given New Zealand's seasonal pasture-based dairy systems, this review aims to summarise existing findings and identify knowledge gaps regarding the impact of calf rearing on the full lactation performance of dairy cows from calving to dry-off.

2.1. New Zealand dairy production system

2.1.1. Pasture-based

New Zealand offers a unique climatic condition that supports the optimal seasonal growth of high-quality pastures, containing all the nutrients for ruminant animals. Embracing the comparative advantage of natural resources, the country predominantly practices a pasture-based dairy production system. Grazing pasture with minimal to no supplements is the primary source of feed for dairy cows (Stafford, 2017). This approach contrasts with the dairy production system in many other countries, where an intensive feeding system exists, which involves feeding grains, concentrates, food industry by-products, and conserved forages, and is typically characterised by little or no access to pasture (Stafford, 2017).

From an economic perspective, the pasture-based dairy system is cost-effective and requires less labour than intensive feeding systems, where cows have access to grazing areas, allowing for easier herd management with minimal labour input (Wilkinson et al., 2020).

2.1.2. Seasonal

In New Zealand, seasonal calving occurs in spring (July to September), aligning with the period of optimal pasture growth and supporting the nutritional demands of early lactation (Timlin et al., 2021). During the peak pasture growth period in spring, cows cannot graze the entire pasture on the farm. Instead, effective pasture management involves maintaining an appropriate grazing rotation based on a pasture or feed budget. Therefore, the excess pasture can be conserved as silage or hay to be later utilised in winter and early lactation when the animals have high energy demands or there is a pasture shortage (Roche et al., 2017).

Conversely, dry-off occurs just before winter (around May). The dry period lasts for 2–3 months, during which pasture growth is minimal, aligning with the lower energy requirements for cows as they are not milking (Figure 2). The cows are in their last term of pregnancy at this time (average 280-day (DairyNZ, 2023a), so after the dry period, they start calving and restart the lactation cycle.

Based on genetic merit, health status, and their dam's pasture conversion ratio into milk, only about 25% of the female calves born each season are reared as replacement heifers for future lactation; the rest of the calves are surplus to the requirement (Hickson et al., 2015).

2.1.3 Calf Rearing Systems

The rearing period in dairy farming typically spans from birth to 12 weeks of age and is a crucial phase that can significantly impact the health, growth, and future productivity of dairy calves (Ormond, 2024). The average birth weight of female calves born in dairy farms varies by breed: 36.1 kg for Holstein-Friesian (HF) calves, 27.6 kg for Jersey (J) calves, and 31.7 kg for HF x J crossbred calves (Hickson et al., 2015). Following animal welfare standards, calves should be weaned when they are in good health condition, not receiving animal treatments, and can eat more than 1kg of meal and 2kg of forage (e.g., pasture) per day (NZAgbiz, 2023). The common dairy industry weaning weight is 70 kg for J, 80kg for HF x J, and 90 kg for HF calves (NZAgbiz, 2023).

Calf-rearing systems need to optimise growth, welfare, and economic efficiency. Cow rearing and artificial rearing are the two most common calf-rearing practices in beef and dairy farms, respectively, in New Zealand. However, some dairy farms also have cow-rearing systems, so these will be briefly described below.

2.1.3.1 Artificial Rearing

The most common way of rearing dairy calves in New Zealand is by artificial rearing. This system has become the predominant strategy in commercial dairy production systems, allowing farmers to optimise milk yield and increase farm profitability (Welk et al., 2023). Under this system, calves are taken away from the dam soon after birth (around 24 to 48 hours) and are reared using bucket feeding, artificial teats, or automated milk feeders (Neave et al., 2022).

In an artificial rearing system, calves are typically fed a restricted amount of milk or milk replacer, with approximately 10% of the initial body weight of milk or milk replacer (4-6 litres) being offered (Hu et al., 2020; Khan et al., 2011). This can be administered once a day (OAD) or twice a day (TAD). Once a day can be beneficial in pasture-based systems because of its lower labour requirements and less time spent feeding calves (Eriso & Mekuriya, 2023). However, there might be a slow growth rate and potential digestive issues as a larger volume of milk or feed is consumed by calves at once (Palczynski et al., 2020). Additionally, conventional industry practices such as restricted milk feeding and encouraging early rumen development have been linked to increased hunger-driven behaviours, negative welfare outcomes, and reduced playfulness (Krachun et al., 2010).

Another approach to artificial rearing provides calves with unrestricted access to milk in an *ad libitum* feeding system, which supports fast growth (0.8–1.2kg/day) and high immune function, resulting in high body weight at the time of weaning (Bach et al., 2007). However, calves fed *ad libitum* often have a longer weaning period, averaging 13 weeks (Cuttance et al., 2017), and consume a larger volume of milk, which reduces the amount of milk available for the market.

For example, the research conducted by Jasper and Weary (2002) reported that dairy calves fed *ad libitum* consumed 89% more milk over the first four weeks and gained 63% more body weight at weaning than calves fed a restricted milk volume. Additionally, *ad libitum* milk feeding has been associated with enhanced pre-weaning growth and better welfare, underscoring the necessity of nutrition-based welfare optimisation.

Among artificial rearing techniques, group housing with automated feeders has become a progressive approach that provides customised feeding control and social enrichment (Fujiwara et al., 2014), although there are increased risks of disease transmission and competition for feeding access (Sinnot et al., 2022). One of the major issues with artificial rearing is the weaning stress, since a sudden stop in milk feeding causes disrupted feeding patterns and increased suffering (Khan et al., 2007). Therefore, a gradual decline in milk availability is recommended as it has been demonstrated to reduce stress responses, promote solid feed consumption, and sustain post-weaning growth (Vogt et al., 2024).

2.1.3.2 Cow Suckling

Natural or cow suckling is mostly practised in beef farms and low-input dairy systems, where calves stay with and are nursed by their mothers. Calves that are reared by the dam without disturbance will suckle their dam approximately 8–12 times/day for 10 minutes each time (Reinhardt & Reinhardt, 1981) and show an average daily gain of up to 1.2 – 1.4 kg/day in the first 3 months of age (Flower & Weary, 2001). Calf rearing on foot facilitates better pre-weaning weight, largely due to *ad libitum* milk intake (Bryant et al., 2024). In cow suckling, around 20% of the initial body weight is offered (Khan et al., 2011).

This cow suckling system is featured as enhanced calf welfare that facilitates the natural establishment of cow-calf bonds, supports immune system development, and fosters superior growth rates (Verdon & Tilbrook, 2021). Prolonged interaction between cows and calves is associated with long-term welfare benefits such as improved social behaviour, reduced abnormal behaviour, and decreased stressor reactions (Meagher et al., 2019). Cows that are permitted to nurse their calves can exhibit longer lactation and better udder health, most likely as a result of the increased oxytocin-mediated milk secretion (De Passillé et al., 2008). This system may potentially support better mammary gland development (Vailati-Riboni et al., 2018).

Despite these behavioural and physiological benefits, natural suckling is not widely practised in commercial dairy farms in New Zealand. The direct consumption of a dam's milk by calves results in less saleable milk yields, which is not economically viable for large-scale dairy industries (Marley et al., 2010). For example, research conducted by Mac et al. (2022) in Australia found that while calves were kept with cows, the average milk yield was 12±7.6 kg/day 3 days before weaning, and the milk production increased up to 31±8.3 kg/day after weaning, indicating that milk consumption by calves was close to 20 kg per calf per day. This demonstrates the large volume of milk consumed by calves in natural suckling practice, which would otherwise be available for the market. Furthermore, the separation of cow-calf at delayed weaning (8–12 weeks) can result in severe distress, which may induce behavioural changes and growth setbacks (Verdon & Tilbrook, 2021).

2.2. Milk Production Physiology

Milk Production in dairy cattle is a complex physiological process influenced by hormonal regulation, management practices, and environmental conditions. The various stages involved in this process are mammary gland development (mammogenesis), initiation of milk production (lactogenesis), milk ejection, and involution.

2.2.1 Mammary gland development (Mammogenesis)

Mammogenesis is the process of growth and structural development of the mammary glands, involving several stages: fetal, prepubertal, pubertal, pregnancy, early lactation, and involution (Geiger & Hovey, 2023). The process begins during fetal development, with gradual growth continuing through the prepubertal and pubertal stages. During puberty, hormones such as estrogen, growth hormones, and insulin-like growth factor 1 (IGF-1) play a vital role in the formation of the ductal system in the mammary gland, thereby supporting future milk synthesis (Macias & Hinck, 2012). Mammary development accelerates significantly (around 90% faster) during pregnancy, particularly in the last three months, reaching its peak in preparation for lactation, where progesterone and prolactin stimulate alveolar formation (Macias & Hinck, 2012; Mukherjee et al., 2023).

The development of the mammary gland is influenced by various factors, including hormonal changes, genetics, receptor expression, intracellular signalling, environmental stressors such as heat stress, and nutritional status (Vang et al., 2024). Additionally, overfeeding can lead to excessive fat deposition in the mammary gland, which limits glandular development, while underfeeding results in poor ductal and alveolar growth (Lohakare et al., 2012). These factors subsequently impact the function and number of epithelial cells, affecting milk production capability. Therefore, it is essential to monitor and control the nutritional intake of young dairy cows to ensure optimal mammary development and future milk production potential. Technological advancements in imaging techniques, such as ultrasound to measure parenchymal depth, could facilitate better monitoring of mammary development over time and help in selecting cows with better milk production potential (Vang et al., 2024).

During early lactation, the mammary gland becomes fully functional, actively synthesising and secreting milk in response to hormonal signals and suckling stimuli. This is followed by involution, during which milk production ceases, and alveolar cells undergo apoptosis for tissue regression and preparation for the next reproductive cycle (Mukherjee et al., 2023).

2.2.2 Initiation of milk production (Lactogenesis)

Lactogenesis, or the beginning of the milk secretion, involves several changes to the mammary epithelium required to transition from an undifferentiated mammary gland during early pregnancy to full lactation (Neville et al., 2001). The process is initiated by the hormonal shifts of prolactin and progesterone during parturition, which enable mammary epithelial cells to begin milk synthesis. Lactogenesis occurs in two stages:

Lactogenesis I: This phase occurs during the late gestation period when the rising prolactin levels stimulate mammary epithelial cells to undergo differentiation and begin the synthesis of milk components such as casein and lactose (Neville et al., 2001). However, the secretion of milk is inhibited by high circulating progesterone concentration. During this phase, the production and accumulation of nutrient-rich immunoglobulins and protective proteins like lactoferrin-containing milk-like liquid named colostrum takes place in preparation for the newborn calf's immune protection (Silva et al., 2024).

Lactogenesis II: This phase usually begins before or shortly after parturition (24–48 hours) in dairy cattle and signals abundant milk production, where prolactin and oxytocin play a key role in stimulating milk and milk ejection, respectively (Macias & Hinck, 2012). The phase is activated by a prolonged rise in prolactin and a significant drop in progesterone. This hormonal change encourages mammary epithelial cells to close their tight junctions, increasing milk volume and significantly changing the composition of milk (Neville et al., 2001). Once milk secretion becomes stable and is sustained by regular milking or suckling, the process transitions into galactopoiesis, the maintenance phase of milk production (Akers, 2006).

2.2.3 Milk Ejection

Milk ejection in dairy cows is initiated by tactile stimulation of teats, which transfers a neural signal to the brain, activating the release of oxytocin from the posterior pituitary (Bruckmaier, 2001). This hormone stimulates the contraction of myoepithelial cells around the alveoli, facilitating the transfer of milk through the duct system (Crowley & Armstrong, 1992). The lag time from stimulation to milk ejection is typically 1–2 minutes, influenced by the degree of udder fill and lactation stage. Conversely, lag time may be longer in late lactation (Bruckmaier & Hilger, 2001).

Oxytocin release remains continuous throughout the milking, promoting efficient milk removal. However, even with a complete oxytocin response, a portion of milk known as residual milk normally remains in the udder after milking (Bruckmaier & Hilger, 2001). If oxytocin release is insufficient or delayed, the volume of residual milk can increase significantly, resulting in a reduction in overall milk yield (Isaksson & Arnarp, 1988). The udder typically refills in 12 hours after previous milking, which varies depending on the milking frequency and stage of lactation (Bruckmaier, 2001). The process of milk transfer into the cisternal compartment increases with time from previous milking, and this transfer is highest at peak lactation and decreases towards the end of lactation (Bruckmaier & Hilger, 2001).

2.2.4 Involution

Involution in dairy cows occurs during the transition from a lactating to a nonlactating phase and begins after the cessation of milk removal (Hurley, 1989). This process involves hormonal changes, particularly a decline in prolactin and oxytocin levels, that result in changes in mammary secretion composition and a reduction in the number of milk-secreting cells (Hurley, 1989). Involution can be divided into three distinct stages: active involution (rapid epithelial cell apoptosis and immune cell infiltration), steady phase (gland remains non-secretory or prepares for future lactation), and developmental phase (renewal of epithelial cells that support upcoming colostrum secretion) (Jaswal et al., 2022).

Dairy cows require a nonlactating or dry period between successive lactations to maximise milk production in subsequent lactations (Collier et al., 2012). The generally recommended dry period for dairy cows is 45–60 days, with a nonlactating period of less than 40 days resulting in decreased milk yield in subsequent lactation (Collier et al., 2012; Swanson, 1965).

2.3 Milk Composition

2.3.1 Colostrum

Colostrum is the first milk produced by the mammary gland during late gestation and within the first 24 hours after calving, and it contains growth hormones, immunoglobulins (IgG), and essential nutrients that promote early development and immunity of newly born calves (Godden, 2008). From an economic perspective, colostrum is not a saleable product but is important for calf health and survival.

Since calves are born without immune protection, the timely intake of colostrum is crucial for transferring passive immunity. Calves should have taken colostrum within the first two hours after birth and by six hours at a maximum, with a concentration $\geq$ 50 mg/mL of IgG, and calves should consume approximately 10–15% of high-quality colostrum of their body weight for optimal protection (Lopez & Heinrichs, 2022). Colostrum that is surplus to calves' immediate need at birth and not saleable can be collected and stored for later use, especially for calves that are artificially reared, including those that were deprived of enough colostrum from their mother (Godden, 2008). To obtain higher-quality colostrum, farmers should aim to milk cows within one to two hours after calving, with a maximum delay of six hours (Godden, 2008).

2.3.2 Colostrum vs Milk

While colostrum is often referred to as first milk, it differs significantly from mature milk in both composition and biological function. After 24 hours of lactation, the milk is called transition milk, which still contains higher levels of antibodies and nutrients than mature milk (Godden, 2008). However, these levels decrease with each subsequent milking, usually until 3–5 milkings or 2–4 days postpartum, when mature milk is secreted.

The composition of colostrum and mature milk differs in function as well as physical and chemical properties. The concentrations of biologically active substances (IgG, hormones, growth factors such as insulin-like growth factors IGF-1 and IGF-2, enzymes, etc.) and several nutrients (proteins, minerals, vitamins, etc.) are multiple times higher in colostrum compared to milk (Georgiev, 2008). Table 1 below highlights key nutritional and bioactive components in dairy cows' colostrum and mature milk.

Table 1: Comparative composition of colostrum and mature milk in dairy cows.

Component	Colostrum	Mature Milk	Sources
Water	72–76%	87–88%	Silva et al. (2024)
Total Protein	16.8% (168 mg/ml)	3.2–3.5 % (32–35 mg/ml)	Puppel et al. (2019)
Casein	4.1% (41 mg/mL)	2.6–2.8% (26–28 mg/mL)	Puppel et al. (2019)
Whey Proteins	12.7% (127 mg/mL)	0.6–0.7% (6–7 mg/mL)	Puppel et al. (2019)
Fat	6.7% (67 mg/mL)	4.6–4.7% (46–47 mg/mL)	Puppel et al. (2019)
Lactose	2.9% (29 mg/mL)	4.5–5% (45–50 mg/mL)	Gambelli (2017)
IgG[1]	41–97 mg/mL	<0.1 mg/mL	Coleman et al. (2015)
IGF-1[2]	0.2–2 mg/L	<0.01 mg/L	Mero et al. (1997)

[1]IgG = Immunoglobulin G, [2]IGF-1 = insulin-like Growth Factor 1

Alongside compositional properties, somatic cell count (SCC) is another indicator that determines milk quality, udder health, and the price of raw milk within the dairy industry (Moon et al., 2007). Somatic cells are primarily leukocytes (95%) and are counted per millilitre of milk. Somatic cell count of > 100,000 cells/ml is often considered to be normal, reflecting a healthy mammary gland, whereas an SCC of > 200,000 cells/ml typically signals bacterial infection or subclinical mastitis, even when no visible symptoms are present (Bradley & Green, 2005). High SCC levels can negatively impact milk production, shelf life, and processing properties.

A range of instruments or technologies is used to measure and monitor SCC. On-farm SCC instruments include SenseHub Dairy SCC Sensors (SENSEHUB®), DeLaval Cell Counter, Lely MCQ-C, Mastatest SCC1 Test Kit. Laboratory SCC instruments include Bentley Instruments (e.g., Combi 150, FTS/FCM) and Foss BactoCount and BacSomatic (BACTOSCAN®). Routine SCC monitoring enables early detection of infections, helps in maintaining milk quality standards set by regulatory authorities, and supports animal welfare (Vieira et al., 2021).

2.3.3 Mature Milk

Cows' milk is a complex nutrient-rich biological liquid, composed mainly of water (approximately 87.4%) and milksolids (12.6%), which include carbohydrates, fats, proteins (casein, whey), vitamins, and minerals (Geary et al., 2010; Taylor & Kabourek, 2003). The major carbohydrate (disaccharide) found in milk is lactose (around 4.8%), which provides energy and supports calcium absorption (Gambelli, 2017). Minor sugars include glucose, galactose, and oligosaccharides.

Milk fat (constituting about 3.5–5.5%) is primarily made of triacylglycerols and is naturally dispersed in milk as tiny droplets in an oil-in-water emulsion, and contains over 400 fatty acids (Lindmark Månsson, 2008). These include saturated (e.g., palmitic acid), monounsaturated (e.g., oleic acid), and polyunsaturated fats (e.g., linoleic acid and CLA), along with phospholipids, sterols, and free fatty acids (Taylor & Kabourek, 2003). Fat not only provides a concentrated energy source but also supports the absorption of fat-soluble vitamins like A, D, E, and K (Voronina et al., 2022). Milk proteins (3–4%) consist of caseins (about 80%) and whey proteins (about 20%), which help in calcium transfer, immunological support, and muscle maintenance (Bielecka et al., 2022). Furthermore, milk minerals, which include calcium, phosphorus, magnesium, sodium, and potassium, are essential for bone tissue formation, fluid balance, and nerve function (Voronina et al., 2022). Also, vitamins in milk, including both fat-soluble and water-soluble (e.g., vitamin C and B-complex), play key roles in metabolism, immunity, and growth (Voronina et al., 2022). Altogether, these components make cow's milk a crucial input in the dairy nutrition and processing industries.

The average milk composition in New Zealand dairy cows includes 86.69% water, 4.39% fat, 3.65% protein, 4.67% lactose, and 0.60% minerals (Table 2). Composition varies with breed, physiology (age, parity), diet, and environmental conditions (Linn, 1988). For example, J milk is richer in fat and protein compared with HF milk (Table 2).

Table 2: Milk Composition (%) of Holstein-Friesian (HF), Jersey (J), and the average milk composition in NZ dairy cows. Source: Geary et al. (2010)

Milk Component	Holstein-Friesian	Jersey	New Zealand
Water	87.74	85.48	86.69
Fat	3.83	5.33	4.39
Protein	3.34	4.06	3.65
Lactose	4.49	4.53	4.67
Minerals	0.60	0.60	0.60

Milk is a commercially valuable product and forms the primary source of income on dairy farms, particularly in New Zealand, where payment is based on milksolids rather than volume. This system reflects the economic importance of milksolids in the manufacture of high-value dairy products such as cheese, butter, milk powders, yoghurt, and protein concentrates, which serve both nutritional and industrial purposes. As a result, most farmers aim to maximise milksolids production to enhance profitability, rather than allocating milk for calf-rearing.

Table 3: Nutritional composition of various dairy products (g/100g of final product). Source: Sneddon et al. (2015)

Component	WMP[1]	SMP[2]	Cheese	Butter	Casein	MPC[3]	WP[4]	BMP[5]
Fat	26.50	1.00	35.00	84.00	0.00	0.00	1.00	8.30
Protein	25.10	33.00	24.50	0.59	89.00	90.50	15.15	41.72
Lactose	39.80	54.00	1.39	0.79	0.56	Trace	77.15	40.32
Minerals	5.90	8.00	2.15	0.12	0.80	Trace	4.32	4.66
Water	2.70	4.00	35.26	14.50	9.64	9.50	2.38	5.00

[1]WMP=whole milk powder, [2]SMP = skim milk powder, [3]MPC=milk protein concentration, [4]WP=whey powder, [5]BMP = butter milk powder.

2.4 Lactation Curve

A lactation curve reflects the pattern of milk production during the lactation period in dairy cows (Wood, 1967). A typical lactation curve of milk production can be divided into three phases: an increasing phase between calving and peak yield (early lactation), a maintaining phase of peak yield, and a decreasing phase after peak yield and dry-off (late lactation) (Gengler, 1996).

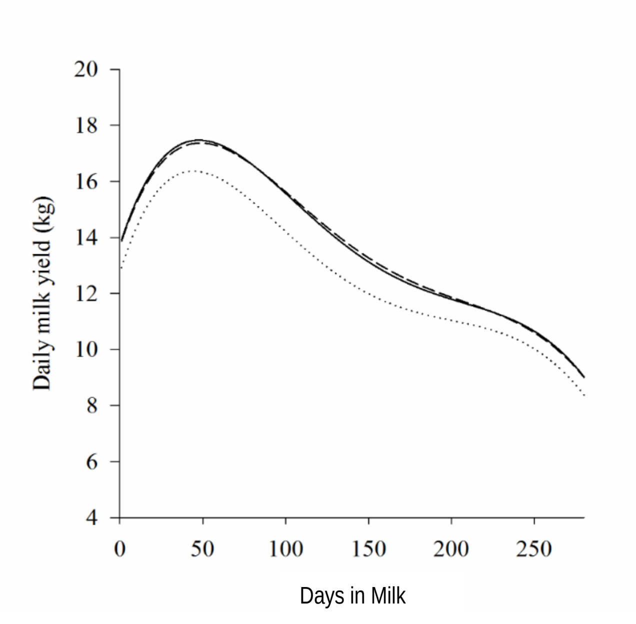

Figure 1: A 270-day lactation curve for Holstein-Friesian (HF: --), Jersey (J; ···), and HF x J (-) cows in New Zealand. Source: (Sneddon et al., 2016a)

During the early lactation phase, milk production gradually increases as lactogenesis is fully established. The lactation curve in NZ is closely aligned with seasonal pasture growth, driven by the predominance of spring calving (Back & Sneddon, 2023; Farrell et al., 2023). Under this system, dairy cows generally show an average lactation period of 270 days and a peak yield after 6–8 weeks of lactation, supported by peak pasture growth and optimal hormonal activity, and is followed by a gradual decline in milk production due to progressive mammary gland involution (Back & Sneddon, 2023; Sneddon et al., 2016a). Also, persistency is an essential parameter in the lactation curve, defined as the ability to maintain the level of milk production during lactation (Jiang et al., 2020).

Several factors, including genetics (breed), physiological (age, parity, and health status), environmental (pasture growth), and management (feed, housing, and milking frequency), can affect the structure of the lactation curve (Jiang et al., 2020). The lactation curve is a valuable tool for visualising the pattern of daily milk production throughout a dairy cow's lactation period, helping to quantify the effects of these factors on overall milk yield (Wood, 1967).

2.5. Factors Affecting Milk Yield, Milk Composition, and Lactation Curve

2.5.1 Seasonal Variation

The seasonal variation in milk composition and milk production is due to changes in the stage of lactation as well as in the feed (Bansal et al., 2009). Cows produce more milk during early lactation in spring when pasture growth is abundant, and cows reach peak milk yield (Figure 2). However, the concentration of milksolids (fat and protein) is lower, mainly due to the dilution effect caused by the higher milk volume (Auldist et al., 2017). As the lactation progresses towards late lactation, there is a decrease in milk volume but an increase in milksolids concentration (Auldist et al., 1998; Bansal et al., 2009). Overall, the production of total milksolids decreases due to the more significant reduction in milk volume. Notably, in seasonal systems, the stages of lactation and season are closely aligned, making it challenging to isolate the effects of each. This relationship highlights the importance of pasture growth and its timing in determining milk production patterns in the NZ dairy system.

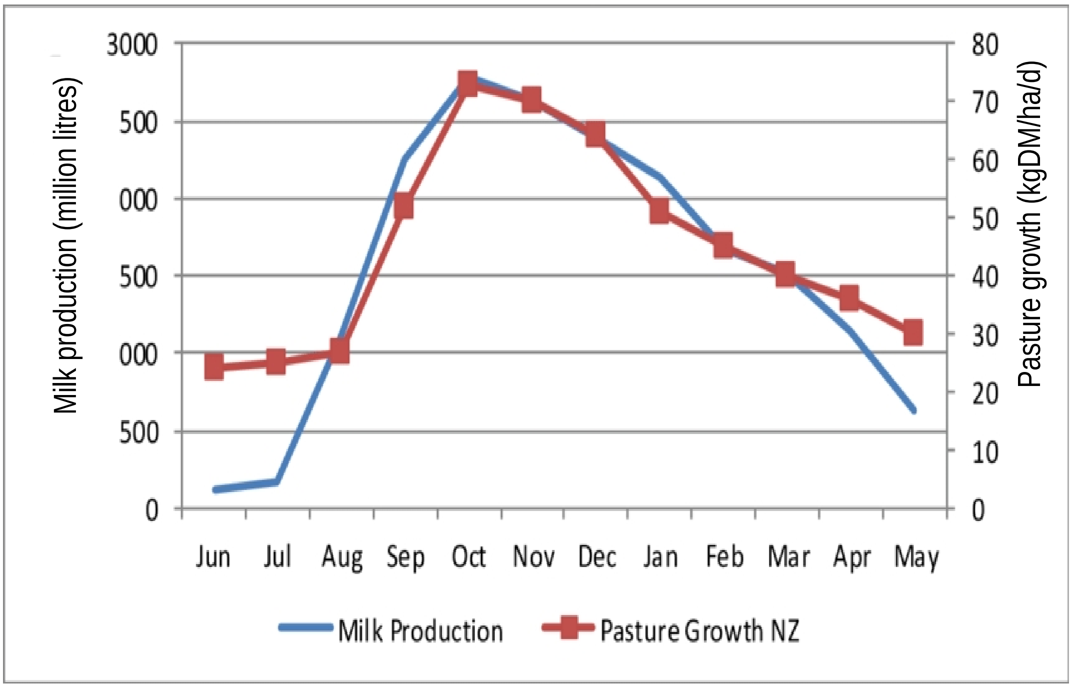

Figure 2: Typical curves of milk production (blue line, millions of litres per month) and pasture growth (red line, kilograms of dry matter per hectare per day) for New Zealand. Source: Shadbolt and Apparao (2016).

2.5.2 Parity

Parity refers to the number of lactations in dairy cows. Milk production is influenced by the number and activity of mammary epithelial cells, regardless of the stage of lactation (Miller et al., 2006). Milk yield is generally higher in multiparous (parity 2-5) cows because of well-developed mammary glands than in primiparous (parity 1 or first lactation) cows (Miller et al., 2006; Wathes et al., 2007). Multiparous cows consistently achieve higher peak yields than primiparous cows at the beginning of lactation, followed by a continuous decrease in milk yield (Figure 3).

In contrast, persistency is usually higher in primiparous cows (Chen et al., 2024). The persistency of lactation is almost the same throughout the lactation period in primiparous cows and fluctuates over time in multiparous cows (Miller et al., 2006). This differentiation is due to the differences in the mammary gland and metabolic demands between the parties.

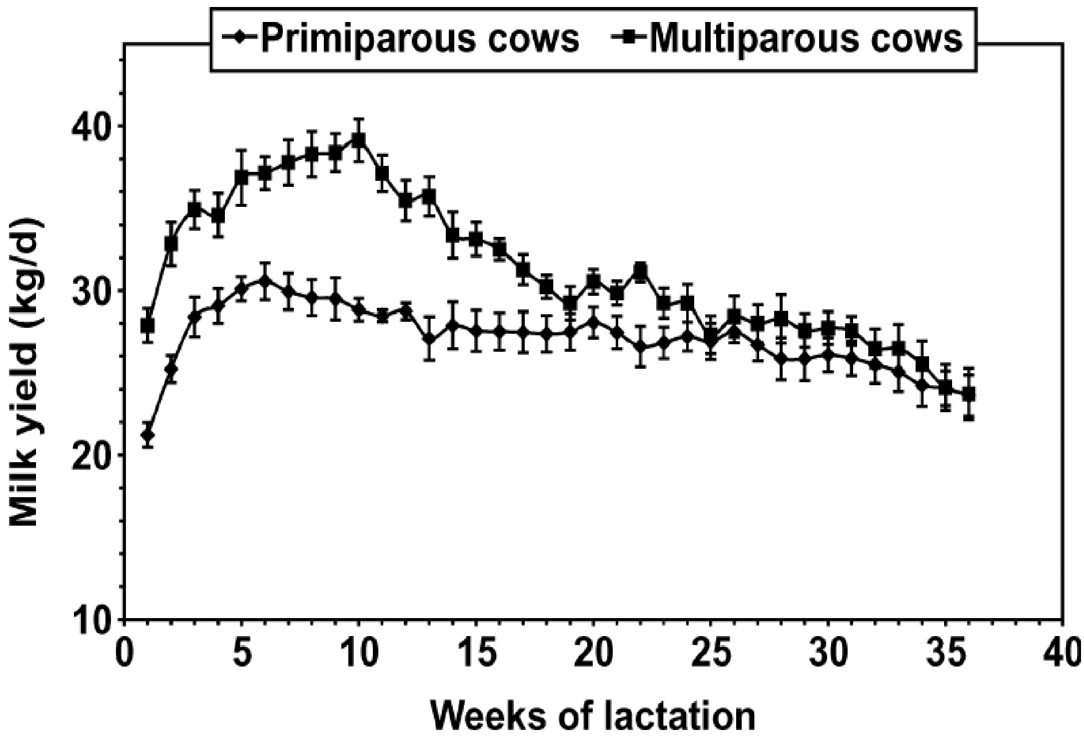

Figure 3: Parity effect on milk yield and persistency. Source: Miller et al. (2006)

2.5.3 Breed

Breed plays a crucial role in determining milk yield, composition, and the shape of the lactation curve in dairy cows. Different breeds have varying milk production levels and milk compositions. For example, HF cows typically exhibit the highest milk volume yield but have the lowest concentrations of fat and protein, while Jersey cows produce less milk but with the highest fat and protein (Sneddon et al., 2016a). Crossbreed (HF X J) cows achieved intermediate curves, with an optimal balance between milksolids and volume (Prendiville et al., 2011). This result supports the use of crossbreeding strategies in New Zealand, where farmers are paid based on the milksolids production rather than milk volume, thus optimising both production efficiency and economic return (Bryant et al., 2024).

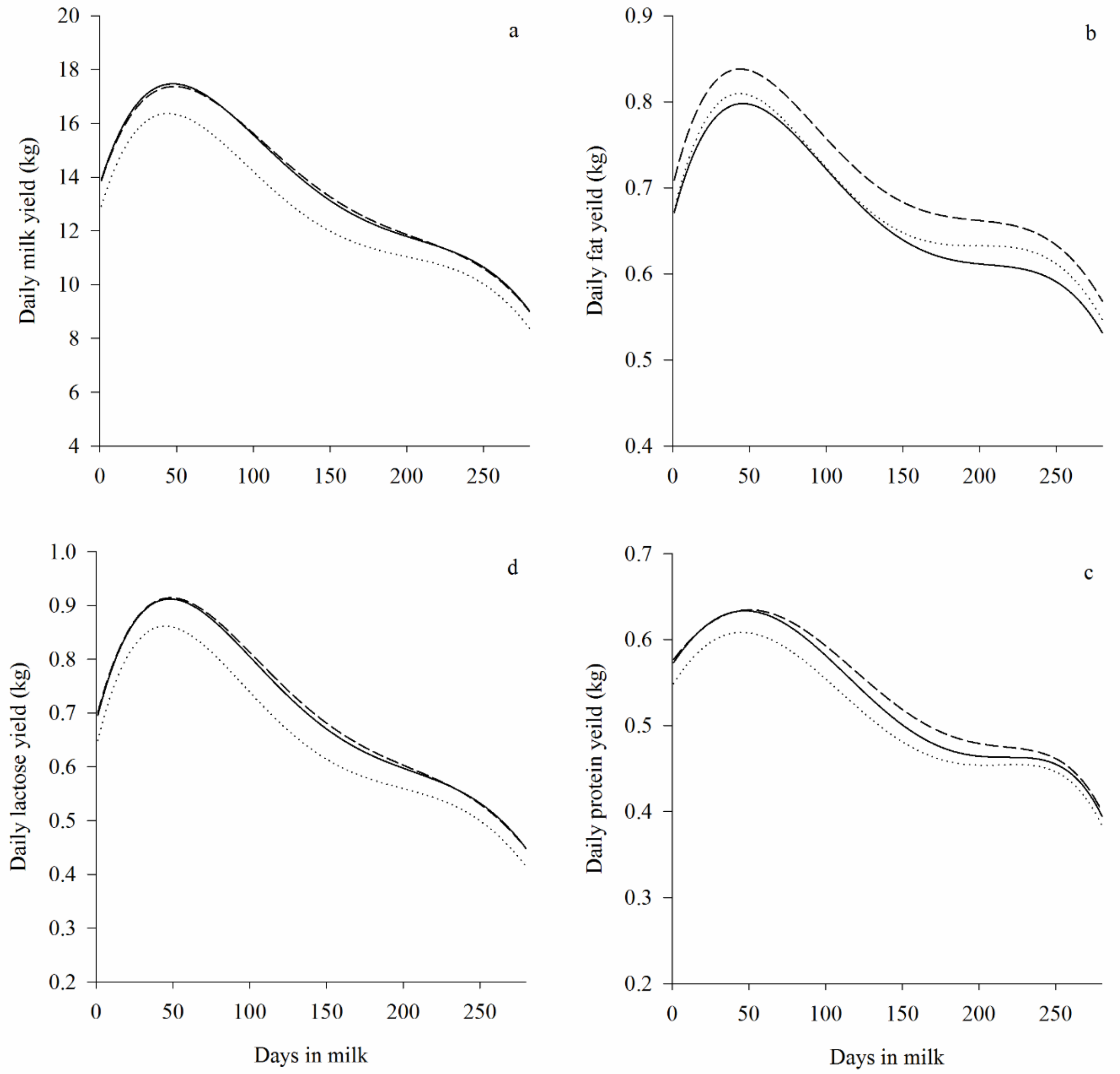

Figure 4: 270-day lactation curves for milk (a), fat (b), protein (c), and lactose (d) yield for first-lactation Holstein-Friesian (HF: -), Jersey (J; ⋯), and HF x J (- - -) crossbred cows in NZ dairy herds in the 2010–11 dairy season. Source: (Sneddon et al., 2016a)

2.5.4 Milking Frequency

The most practised milking systems in NZ are twice-a-day (TAD) or once-a-day (OAD). Milking TAD is typically performed at 10 to 14-hour intervals in the morning and afternoon, supporting higher milk production. In contrast, the OAD milking system is practised only in 10% of NZ herds (Edwards, 2018), mainly as a strategy to improve cow welfare and lower labour costs.

Flexible milking strategies, such as adjusting milking intervals or switching between OAD and TAD, are increasingly adopted in New Zealand to improve labour efficiency and staff wellbeing. A national survey showed that TAD milking required up to 58% of a 40-hour work week per worker, while OAD reduced this to as low as 18% (Edwards et al., 2020). Shortening milking intervals to 8/16 hours (instead of 10/14) also helped avoid starts before 5 a.m., improving flexibility for workers (Edwards et al., 2020).

Milking frequency influences the shape and persistency of the lactation curve. TAD milking supports a higher milk yield and more persistent lactation curve, while OAD milking leads to a lower milk yield and a more rapid post-peak decline, thereby reducing overall lactation persistency (Murphy et al., 2023).

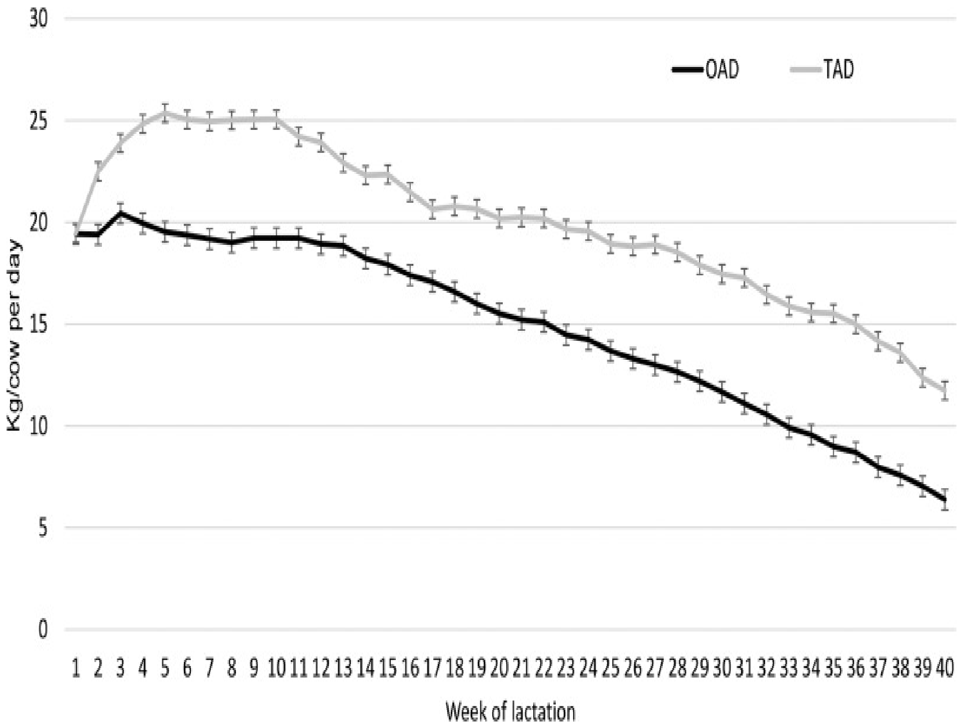

Figure 5: Comparison of once-a-day (OAD) and twice-a-day (TAD) milking of spring-calving pasture-based system. Source: Murphy et al. (2023)

2.5.5 Calf-rearing methods

While calf-rearing systems and their impact on milk yield and cow-calf physiology are described in detail in section 2.1.3, they are also considered a crucial factor influencing the lactation performance of dairy cows. Specifically, having or not having calves at foot during early lactation may affect the yield dynamics, milk composition, and the shape of the lactation curve throughout the whole lactation (Bryant et al., 2024).

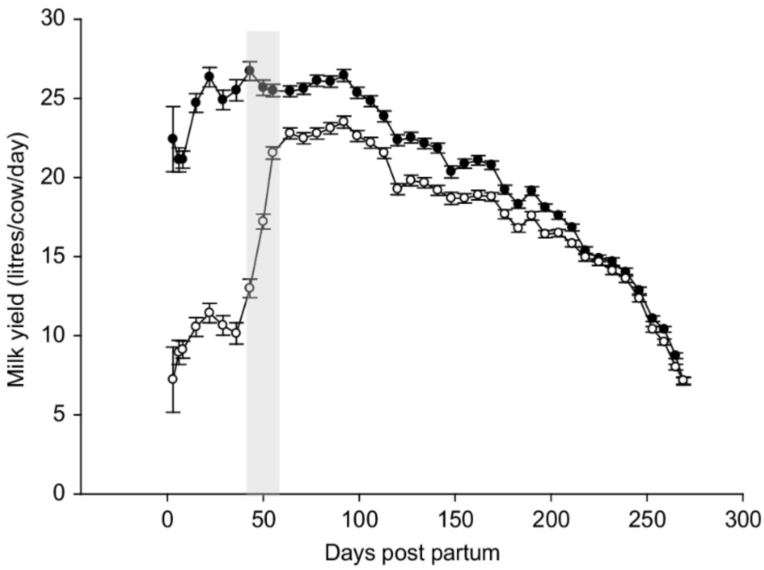

Figure 6: Average milk yield for cows in natural suckling (open symbols) and artificial rearing (solid symbols). The shaded area shows the weaning period. Source: Bryant et al. (2024)

Figure 6 compares the milk yield over time of cows whose calves were allowed *ad libitum* natural suckling versus those whose calves were weaned earlier and reared with restricted feeding. The figure illustrates a significant increase in saleable milk yield immediately after weaning in cow-reared groups, highlighting the calf's direct milk consumption during early lactation. However, whether this early trade-off in saleable yield is compensated later and whether it influences total milk production or lactation persistency over the full lactation remains uncertain. This can be addressed by comparing lactation curves and yield totals between cow suckling and artificially rearing groups.

Studies have shown that natural suckling alters not only the quantity but also the composition of milk, often resulting in higher fat and immunoglobulin levels compared to machine-milked cows (Barth, 2020). The presence of the calf stimulates oxytocin release through sensory interaction, promoting more complete milk ejection than machine milking (De Passillé et al., 2008). By contrast, machine milking may leave more residual milk in the udder due to less effective hormonal stimulation (Isaksson & Arnarp, 1988). Additionally, calves tend to suckle more frequently and variably than cows are milked, which may enhance mammary stimulation and delay involution, potentially influencing lactation persistency and the shape of the lactation curve (Wall & McFadden, 2012). These physiological differences between cow-suckling and artificial rearing warrant further investigation.

While existing research shows that cows nursing their calves produce less saleable milk in the short term, the long-term productivity remains uncertain. Further studies are needed to investigate the impact of various rearing methods on long-term milk productivity, lactation duration, and farm profitability and productivity. A clear understanding of these factors is essential to resolving the uncertainty surrounding the effect of different rearing methods on cow milk production.

2.6. Summary and conclusion from literature review

Effective calf-rearing strategies are crucial for ensuring the long-term productivity and sustainability of dairy farming systems. Natural rearing supports better physical and cognitive development in calves and may enhance lactation performance in dairy cows; however, it reduces the amount of milk sold in the short-term while calves nurse directly from cows. Conversely, artificial rearing increases short-term milk production that can be sold but may affect the growth of calves. Each system has distinct advantages and disadvantages, making it essential to evaluate its impact not only on calf outcomes but also on the dam's milk production, particularly in the context of intensifying dairy farming.

2.7 Research Aim, Questions and Hypothesis

The objective of this research project was to explore how two calf-rearing systems, natural (dam-suckling) versus artificial (hand-rearing or teat feeding), influence the dam's milk production during the lactation period. The treatments were the Cow group, where calves remained with their dams and suckled (natural suckling), and the Shed group, where calves were separated from their dams at birth and reared artificially. The milk production parameters studied were saleable milk yield, components yield (fat, protein, and milksolids), lactation curve characteristics (gradual increase, peak yield, persistency, and decline), and milk composition (protein and fat) from the Cow and Shed groups.

This study was conducted within a seasonal, pasture-based, once-a-day milking dairy system. The research aimed to address the following research questions:

Question 1: Is there a significant difference in milk yield during the pre-weaning period (DIM 5–80) between the Cow and the Shed groups?

Hypothesis 1: The Cow group will have lower saleable milk recorded during the pre-weaning period compared with the Shed group.

Question 2: How does the calf-rearing method (Cow vs. Shed) influence the total milk yield across the full lactation period (DIM 5–305)?

Hypothesis 2: Despite lower early yield in the pre-weaning period, cows in the Cow group will compensate after weaning and achieve a similar total milk yield over the full lactation period compared to the Shed group.

Question 3: How does the calf-rearing method (Cow vs. Shed) influence the shape and persistency of the lactation curve?

Hypothesis 3: The lactation curve of the Cow group will show a delayed peak and greater persistency compared to the Shed group, which is expected to reach an earlier peak followed by a steeper decline.

Question 4: Do the calf-rearing systems (Cow vs. Shed) affect the cumulative yield of fat, protein, and milksolids during the pre-weaning, post-weaning, and overall lactation period?

Hypothesis 4: The calf-rearing method will influence the yield of milk components (fat, protein, and milksolids). Particularly, the Cow group will produce significantly lower pre-weaning fat, protein, and milksolids, but will not differ from the Shed group in post-weaning and overall lactation period.

Question 5: Do the calf-rearing systems (Cow vs. Shed) affect the composition of milk during the pre-weaning, post-weaning, and overall lactation period?

Hypothesis 5: Milk fat and protein concentrations will differ between groups during the pre-weaning phase but are expected not to differ post-weaning and across the full lactation.

3. Materials and Methods

3.1 Animal Ethics Approval

The research was conducted under the approval of Massey University's Animal Ethics Committee (MUAEC), approval number 23/23, as a part of the project titled "Rearing of dairy calves artificially versus suckling on their dams," granted on 16 June 2023. The study formed part of the broader approved calf rearing alternatives project and complied with the Animal Welfare Act 1999 and the Code of Welfare: Dairy Cattle (New Zealand). No procedures were conducted using sedation or anaesthesia, and no animals were euthanised for research purposes.

3.2 Study Location

The study was conducted at Massey University's Dairy No.1 farm, located in Palmerston North (-40.376440147486164, 175.6138119870547), New Zealand. The farm operates a seasonal spring-calving, once-a-day (OAD) milking, and is a pasture-based system typical of the lower North Island, classified as a dairy New Zealand farm system 2 (DairyNZ, 2010). Under this system, the feed was primarily supplied through grazing, consisting of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.), supplemented with conserved forage (pasture silage) as required.

3.3 Animals and Experimental Design

All animals were sourced from Massey University's Dairy No.1 herd and were managed under standard farm practice for nutrition, health monitoring, milking, and housing. The study involved two treatment groups: the Cow group (cows that nursed their calves) and the Shed group (cows that had their calves reared artificially) (Table 4). Each group was initially comprised of 20 dairy cows and their female calves. Later on, due to health issues, one of the cows from the Shed group was removed from the herd. Breed classification was based on recorded breed composition expressed in sixteenths. Cows with ≥ 12 parts out of 16 of a single breed were classified as that breed (HF or J), while cows with a more mixed composition were classified as crossbred (HF x J).

Table 4: Baseline characteristics (number of cows, average age, parity, and breed composition) for the two treatment groups at study commencement.

Trait	Cow Group	Shed Group
Number of cows	20	19
Age (years)	6 ± 2	5 ± 1
Parity	4 ± 2	4 ± 2
Breed	55 % HF[1], 30 % J[2], 15 % HF x J[3]	48 % HF[1], 26 % J[2], 26 % HF x J[3]

Note: Values are mean ± standard deviation (SD). [1]HF = Holstein-Friesian, [2]J = Jersey, [3]HF x J = crossbreed of Holstein-Friesian and Jersey.

3.4 Management of Animals

3.4.1 Cow Management

All cows were managed under the same farm conditions throughout the study. Cows from both treatment groups were part of the same milking herd, were milked OAD at approximately the same time each morning and grazed together with the same pasture rotation. All cows received the same feed allowance, consisting predominantly of perennial ryegrass and white clover pasture, with pasture silage offered when required and were exposed to the same environmental conditions.

3.4.2 Calf Management

Cow group calves: Calves were kept with their dams at all times except during milking, when they were temporarily separated into a dedicated pen with dry woodchip bedding (~1 hour per day). This allowed them unrestricted access to milk through natural suckling, in addition to *ad libitum* access to pasture. Calves were also provided with supplementary calf meal via creep feeders. Weaning occurred when the lightest calf weighed 75 kg, corresponding to a mean age of 68 days (±15 days). Weaning was conducted through a gradual reduction in contact time between the cow and her calf over three days (with 1h, 0.5h, and 0.25 h contact on days one, two, and three, respectively) to decrease the frequency of suckling and transition to weaning.

Shed group calves: The calves in the Shed group were separated from their dams within 36 hours of birth and housed in groups in indoor pens. They were fed 6 litres per day of milk or milk replacer via calfeteria feeders, offered in two feeds, until they were moved to outdoor paddocks, when feed was offered once daily. All calves had *ad libitum* access to calf meal and fresh water from birth. Weaning occurred at a mean age of 96 days, following the farm's standard practice of skipping milk feeding every second day over seven days.

All cows and calves had routine health monitoring, and any health status was recorded. Calf weights were monitored fortnightly to inform growth rates and weaning decisions in both groups.

3.5 Data Collection

Daily milk-yield data for both groups of cows were recorded via an in-shed milking system (DeLaval) from July (calving) until December 2023. These records represented milk available for sale only, as milk consumed directly by calves was not measured. Routine herd tests were performed at approximately monthly intervals, providing two tests per cow before weaning and eight herd tests from weaning to dry-off. All herd test results were downloaded through MINDA (the commercial herd management database system of Livestock Improvement Corporation) and included milk yield, composition parameters (protein, fat, lactose, somatic cell count), and key herd events such as calving and dry-off dates. These data formed the basis for modelling lactation curves and comparing production characteristics between the treatment groups across the lactation period and were later grouped into pre-weaning, post-weaning, and full-lactation phases during statistical analysis.

Study phases: The study was designed to compare milk yield, component yield (fat, protein and milksolids), composition parameters and lactation curve characteristics between the Cow and Shed groups. The analysis covered the entire lactation period with data separated into pre-weaning and post-weaning phases.

Pre-weaning phase: Defined as DIM 5 to weaning for the Cow group and 5 to 80 DIM for the Shed group for the group comparison, as calves in the Shed group were removed within 36 hours of birth and did not suckle. Day 80 was chosen as the cut-off to represent a typical weaning age in New Zealand dairy systems and closely aligns with the mean weaning age observed in the Cow group (68 ± 15 DIM). The milk collected from day 1 to day 4 was considered colostrum or transition milk and was therefore excluded from analysis.

Post-weaning phase: Defined as DIM 1-day post-weaning to maximum DIM for the Cow group and days 81 up to maximum DIM for the Shed group. The transition point between pre- and post-weaning was determined for each cow using the DIM at weaning recorded in the dataset.

3.6 Statistical Analysis

3.6.1 Data cleaning

Records from the first four days in milk were excluded from the daily milk yield dataset, as milk up to the first four days was considered colostrum or transition milk. Likewise, all daily and herd test records with milk yield values below 4 litres per milking were removed as implausible or likely recording errors. Additionally, if daily in-shed milk yield values showed sudden, irregular jumps that were inconsistent with the preceding pattern, they were removed. For example, if consecutive daily yields were 12 litres, 13 litres, and 12 litres for the last three days, but the next day recorded 25 litres, the 25 litres value was counted as erroneous and was excluded. Similar exclusions were applied when a value was approximately double the surrounding yields, which likely reflected recording error rather than true milk production.

However, this adjustment was not applied to data immediately after weaning, since a sudden increase in recorded yield was biologically expected when calves were removed and all milk became available for measurement. Overall, approximately 5% of the total records were removed during data cleaning.

3.6.2 Data analysis in SAS

All analyses were performed in SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Before modelling, datasets were prepared using a combination of PROC IMPORT, DATA steps, and PROC SORT to ensure that variables such as cow number, treatment group, calving date, and days in milk (DIM) were properly aligned. Records were restricted to DIM 5 to 305 (DIM 5 to maximum DIM for the cumulative yield and DIM 5 to 305 for the lactation curve fitting purpose). However, each cow contributed data only up to their individual dry-off dates, such that cumulative yields were calculated using each cow's observed maximum DIM within this window (≤305). Implausible yield values identified during data cleaning (Section 3.6.1) were removed. The transition point between pre- and post-weaning was determined for each cow using the DIM at weaning recorded in the dataset, which allowed for modelling lactation curves separately for each phase and generating a combined curve starting from the weaning point.

Cow group: For the pre-weaning phase (DIM 5 to weaning), daily in-shed milk yield data were used, as only two herd test results were available in this period. This was insufficient to fit a higher-order polynomial model and so yields were plotted directly to describe the lactation pattern. This approach provided a more accurate reflection of the pre-weaning trajectory, as it captured the natural variation associated with calf suckling at different points in time. For the post-weaning phase (DIM 1-day post-weaning to maximum days in milk (≤305)), herd test records provided sufficient observations to fit a fourth-order Legendre polynomial. Polynomial values were calculated as:

$$x = -1+2 \times (DIM- t_{min}) / (MaxDIM-t_{min})$$

$$P0 = 1$$

$$P1 = x$$

$$P2 = ½ * (3x^2-1)$$

$$P3 = ½ * (5x^3-3x)$$

$$P4 = 1/8 * (35x^4-30x^2+3)$$

Models were fitted in PROC MIXED, with fixed effects of treatment and polynomial terms, and cow as a random effect to account for repeated measures. Fixed and random effect values were obtained with the OUTPUT statement. To create a continuous lactation trajectory, pre- and post-weaning curves were joined at each cow's weaning DIM, preserving the sudden rise in yield after calves were removed.

Shed group: Calves were removed at birth, so there was no need to split data into pre- and post-weaning phases. Herd test records from DIM 5 to maximum days in milk (≤305) were analysed as a single dataset. A fourth-order Legendre polynomial was created as described above, and fitted using PROC MIXED, again including cow as a random effect.

The general model used for the analysis was described by Schaeffer (2004) and Pool and Meuwissen (1999).

Yijk = μ + Ti + Pj + Σ (βk Pk(x)) from k=0 to n + Cj + εijk

where Yijk is the milk yield, μ is the overall mean, Ti is the fixed effect of treatment group, Pj is the phase effect (pre- and post-weaning phase), βkPk(x) represents the Legendre polynomial terms of order k, Cj is the random cow effect, and εijk is the residual error. This structure was adapted from standard random regression models to suit the experimental design of the present study.

The same random-regression model and polynomial structure were applied to fat, protein, and milksolids (fat + protein) yields using herd-test records from DIM 5 to 305, because these traits were evaluated across the whole lactation rather than in separate pre- and post-weaning phases.

3.6.3 Graphical Presentation

Predicted means from the mixed models were used to generate lactation curves for each trait and treatment group. For the Cow group, the pre-weaning (DIM 5 to weaning) and post-weaning (DIM 1-day post-weaning to 305) phases were combined into a single trajectory, whereas the shed group was analysed as a single continuous curve from DIM 5 to 305.

Graphs of average predicted lactation were generated in PROC SGPLOT, with both axes set to start at zero for comparability. A vertical reference line was included at DIM 80 to mark the weaning time. Curves for both groups were then plotted on the same scale to enable direct comparison of lactation characteristics and composition parameters.

3.6.4 Calculation of Area Under Curve

The generated graphical outputs were subsequently used for calculating the area under the curve (AUC) using the trapezoidal rule, providing a measure of cumulative yield during the pre-weaning, post-weaning, and overall lactation periods. To quantify cumulative production, the AUC was calculated for milk, fat, protein, and milksolids yields. Separate lactation curves for each trait were used (combined curves were not used for AUC estimation).

The trapezoidal rule was applied to approximate the definite integral of yield with respect to time (DIM). This method was used to calculate the area under each predicted yield curve for each cow, using either daily meter data (for pre-weaning milk yield in the Cow group) or predicted values from the mixed models (for all other traits and phases). AUCs for milk, fat, protein, and milksolids yields were calculated separately for the pre-weaning phase (DIM 5–80), the post-weaning phase (DIM 81–maximum days in milk), and the full lactation period (DIM 5–maximum days in milk (≤305)) for the Shed group. The Cow group's pre-weaning AUCs were truncated at each cow's actual weaning DIM (mean 68 ± 15 days), as recorded in the dataset, so that calculations reflected only the period when calves were suckling. Post-weaning yield was calculated from the day after weaning (weaning DIM + 1 day) to the cow's maximum recorded DIM. Day 80 was used as the standard cut-off to define the pre-weaning phase, representing the typical duration of calves' milk feeding in the New Zealand pasture-based system. Although the average weaning age for the Cow group was 68 ± 15 DIM, the use of 80 DIM provided a consistent time point for comparing phases between treatments.

The shed group's pre-weaning AUCs were standardised to DIM 5–80. This approach enabled valid between-group comparisons while accounting for biological variation in weaning age among calves from the Cow group.

The formula to calculate the AUC was sourced from Trefethen and Weideman (2014) is expressed as:

$$\mathbf{AUC = \sum (from\ i=1\ to\ n-1)\ [(y_i + y_{i+1})\ /\ 2] \times (t_{i+1} - t_i)}$$

Where y_i is the yield at time t_i and n is the number of time points.

The trapezoidal integration was implemented in SAS 9.4 (SAS Institute Inc., Cary, NC, USA) using DATA step programming, which enabled the calculation of AUCs for each cow within the pre-weaning, post-weaning, and overall lactation phases. Group means and standard errors were then obtained from these cow-level AUC values.

3.6.5 Statistical Comparison of AUCs

Area under the curve values for milk, fat, protein, and milksolids yields were analysed in SAS 9.4 (SAS Institute Inc., Cary, NC, USA) using PROC MIXED. Separate models were fitted for the pre-weaning phase, post-weaning phase, and the overall lactation period. The treatment group (Cow vs. Shed) was included as a fixed effect. Because each cow contributed only a single AUC value per phase, an independent (diagonal) covariance structure was applied. Least squares means (LS-means) and their standard errors (SE) were obtained for each treatment group, and pairwise comparisons were used to assess differences between them. Results were presented as LS-means ± SE with corresponding p-values, and statistical significance was declared at $p < 0.05$.

3.6.6 Calculation of Milk Composition

Production-weighted fat percentage (%) and protein (%) were calculated from cumulative yields. Cumulative AUCs for milk, fat, and protein yields were obtained first for each cow and each phase (pre-weaning, post-weaning, and overall lactation) as described in section 3.6.4. Fat and protein percentages were derived as:

Fat% = (Fat yield *100) / Milk yield

Protein % = (Protein yield *100) / Milk yield

These production-weighted percentages represent the average milk composition over each period (pre-weaning, post-weaning, or overall lactation), weighted by actual milk output. For the phase-level analysis, each cow contributed two observations: one production-weighted value for the pre-weaning phase and one for the post-weaning phase.

The percentages were analysed in SAS using PROC MIXED. For phase-level comparisons, treatment (Cow vs. Shed), phase (pre- and post-weaning), and their interactions were considered as fixed effects. Repeated measurements across phases within cows were accounted for by specifying phase as a repeated measure with cow as the subject. For the total lactation means, a separate model included only treatment as a fixed effect.

4. Results

4.1 The cumulative yields of Milk, Fat, Protein, and Milksolids

The cumulative yields of milk, fat, protein, and milksolids for cows that reared a calf or not are presented in Table 5.

Table 5: Cumulative yields (in kilograms/cow, as LS-means ± SE) for milk, fat, protein, and milksolids across the pre-weaning, post-weaning, and total lactation, for cows allocated to the two rearing treatment groups: Shed = cows that had their calves reared artificially and Cow = cows that nursed their calves.

Trait	Period	Cow (LS-means ± SE)	Shed (LS-means ± SE)	P-value
Milk yield	Pre	754 ± 75	1243 ± 75	<0.0001
	Post	2715 ± 189	2461 ± 189	0.3482
	Total	3469 ± 249	3704 ± 249	0.5078
Fat yield	Pre	28.3 ± 2.8	61.76 ± 2.9	<0.0001
	Post	148.5 ± 10.8	132.2 ± 11.1	0.2994
	Total	176.9 ± 12.9	194.0 ± 13.3	0.3648
Protein yield	Pre	25.0 ± 2.1	47.8 ± 2.1	<0.0001
	Post	114.4 ± 8.6	109.5 ± 8.9	0.6952
	Total	139.5 ± 10.2	157.3 ± 10.4	0.2293
Milksolids	Pre	53.5 ± 4.8	109.1 ± 4.9	<0.0001
	Post	263.0 ± 18.4	241.2 ± 19.9	0.4399
	Total	316.5 ± 23	350.4 ± 23.6	0.3113

Note: Values are least squares means (LS-means) ± SE (standard error). Milksolids (fat + protein) were analysed as an independent trait from herd test records. AUC values were calculated directly from the predicted milksolids curves, rather than as the sum of fat and protein AUCs. Total lactation period covered from 5 days in milk (DIM) to the maximum DIM for both groups. For comparison purposes, lactation was divided as follows: the Shed group pre-weaning from 5 to 80 DIM and post-weaning from 81 DIM to maximum DIM; the Cow group pre-weaning from 5 DIM to weaning and post-weaning from day 1 post-weaning to maximum DIM.

4.1.1 Milk Yield

The cows in the Shed group produced 3704 kg of milk over the full lactation (Table 5). Approximately 34% of this milk was produced in the early lactation period (pre-weaning, DIM 5–80), and 66% during mid to late lactation (post-weaning, DIM 81–maximum days in milk). The lactation curve showed a gradual rise to a peak at approximately 100–110 DIM, followed by a steady decline (Figure 7).

The cows in the Cow group produced 3469 kg of milk across the full lactation (Table 5). Around 22% was produced during early lactation (DIM 5 to weaning, Figure 8) and 78% during mid to late lactation (from day 1 post-weaning to maximum DIM, Figure 9). The combined lactation trajectory showed a stable, lower recorded yield during the pre-weaning period, followed by an immediate rise after calves were weaned and a peak at approximately 110–120 DIM (Figure 10).

Figure 8 presents the average lactation trajectory for the cow group pre-weaning, where values were plotted up to each cow's actual weaning DIM. Recorded yields remained relatively stable across the pre-weaning period, with small fluctuations reflecting the variable influence of calf-suckling. A sharp decline was evident from approximately 72 to 80 DIM as cows approached the weaning phase. This occurs because those cows that reared their calves longer (more DIM to weaning) had older and heavier calves and likely suckled a greater quantity of milk, combined with the reduced number of cows contributing to yield data at the end of the phase. This decline does not reflect a true drop in milk production, but rather occurs because fewer cows contributed data, as individual cows were weaned at different time points.

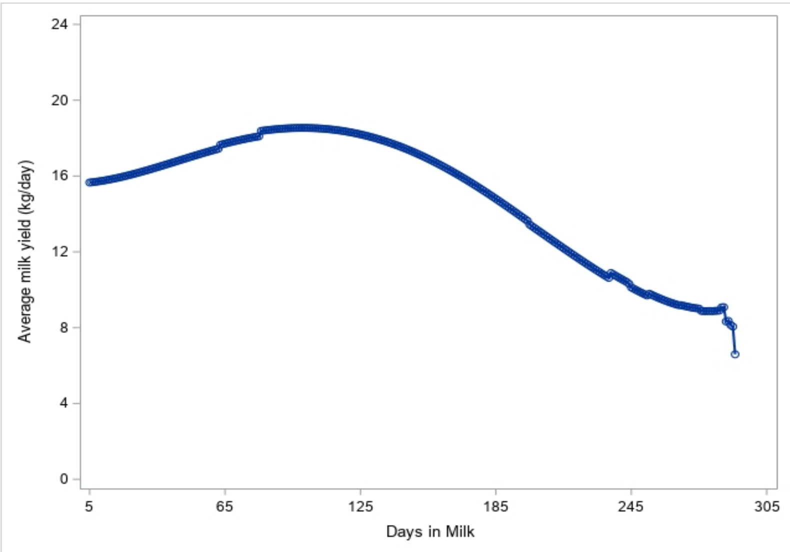

Figure 7: Average milk yield (kg/day) for cows that did not rear a calf (Shed group, n = 19) from 5 to 305 days in milk (DIM), based on 4th order Legendre mixed model fitted to herd test records.

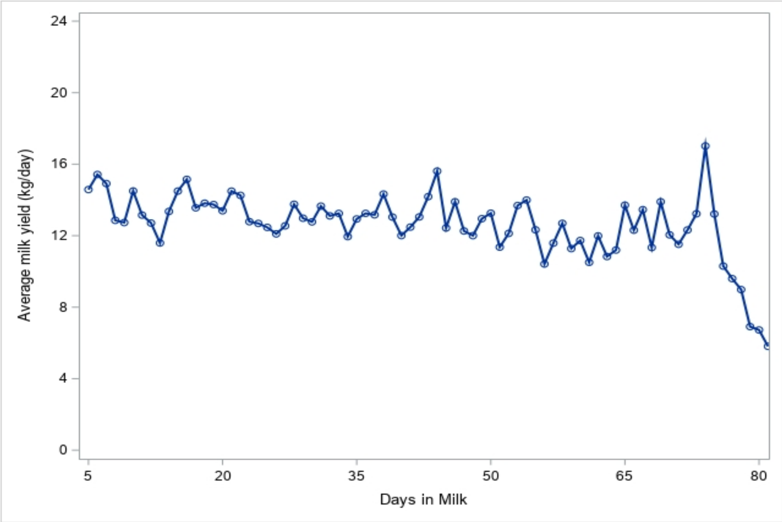

Figure 8: Average milk yield (kg/day) for cows rearing a calf (Cow group, n = 20) from 5 to 80 days in milk (DIM), based on daily meter records. Each cow contributed up to her actual weaning day.

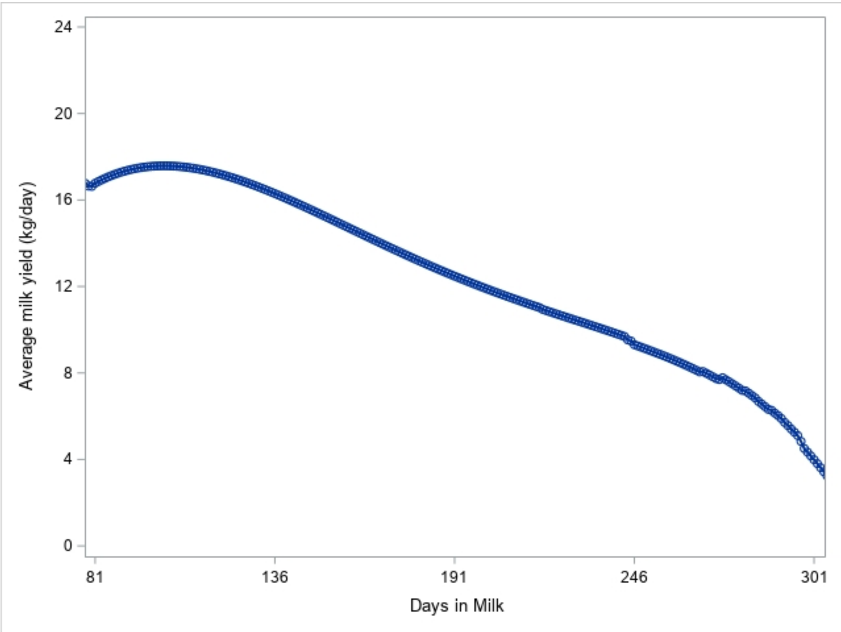

Figure 9: Average milk yield (kg/day) for cows that reared their calves (Cow group, n = 20) from 81 to 305 days in milk (DIM) based on the 4th order Legendre mixed model fitted to herd test records. Each cow contributed from her actual weaning DIM + 1 day to maximum DIM.

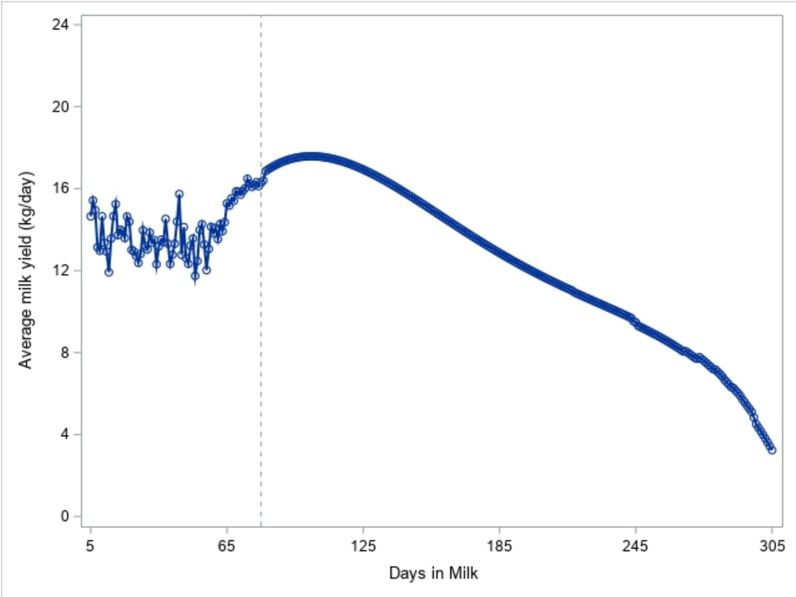

Figure 10: Combined lactation curve for the cows that reared a calf (Cow group) from 5 to 305 days in milk (DIM). The dashed line at DIM 80 marks the industry weaning. Daily meter data were used before weaning, and a 4th order Legendre mixed model was fitted to herd test records after weaning.

During early lactation, the Shed group produced 489 kg more milk than the Cow group, and this difference was significant (Table 5). After weaning, milk yield did not differ significantly between groups, with the Cow group producing a numerically greater post-weaning yield (2715 vs. 2461 kg). Across the full lactation, the Shed group produced 235 kg more milk than the Cow group, but the difference was not significant. The comparison of predicted curves (Figure 11) shows clear separation in early lactation due to calf suckling in the Cow group, followed by convergence after DIM 80. This indicates that reduced recorded milk yield in early lactation for the Cow group was limited to the period when calves were consuming part of their dam's milk.

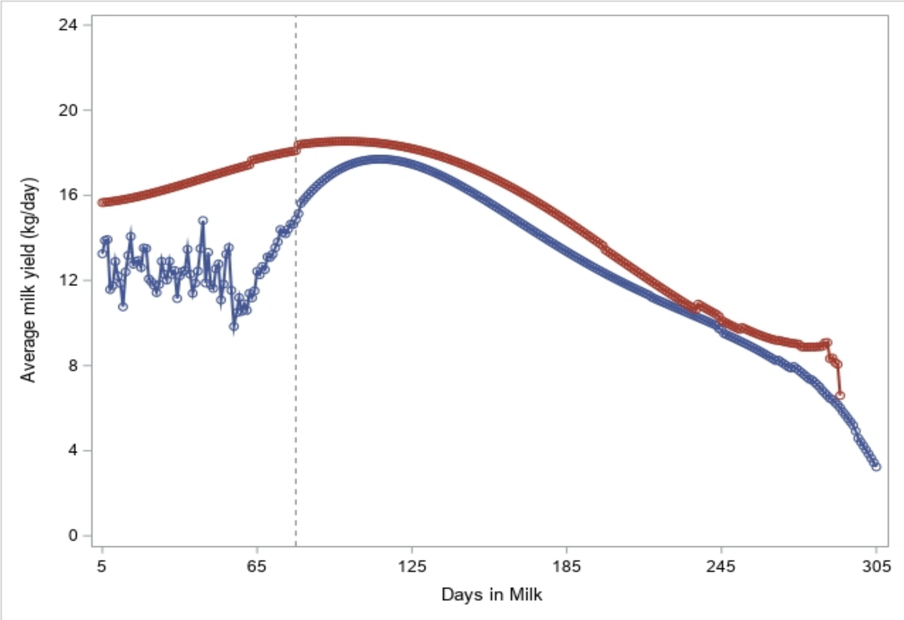

Figure 11: Comparison of average milk yield (kg/day) between the cows that reared a calf (Cow (blue)) and cows that did not rear a calf (Shed (red)) groups across 5–305 days in milk (DIM). For the Cow group, daily meter data were used up to weaning, and polynomial predictions were applied for DIM 81–305. For the Shed group, polynomial predictions were applied for DIM 5–305. The dashed line at DIM 80 marks the industry weaning.

4.1.2 Fat Yield

The cows in the Shed group produced 194.0 kg of milk fat yield over the lactation (Table 5), with approximately 32% being produced during early lactation (the pre-weaning period from 5–80 DIM), and 68% during mid to late lactation (the post-weaning period from 81–305 DIM). The lactation curve showed a smooth trajectory, peaking at approximately 120–130 DIM before declining steadily (Figure 12).

The cows in the Cow group produced 176.9 kg of milk fat over the lactation (Table 5), with approximately 16% being produced during early lactation (DIM 5 to weaning), and 84% being produced during mid to late lactation (DIM 1-day post-weaning to 305). The lactation curve in the Cow group peaked approximately at 140–150 DIM, before showing a gradual decline (Figure 13).

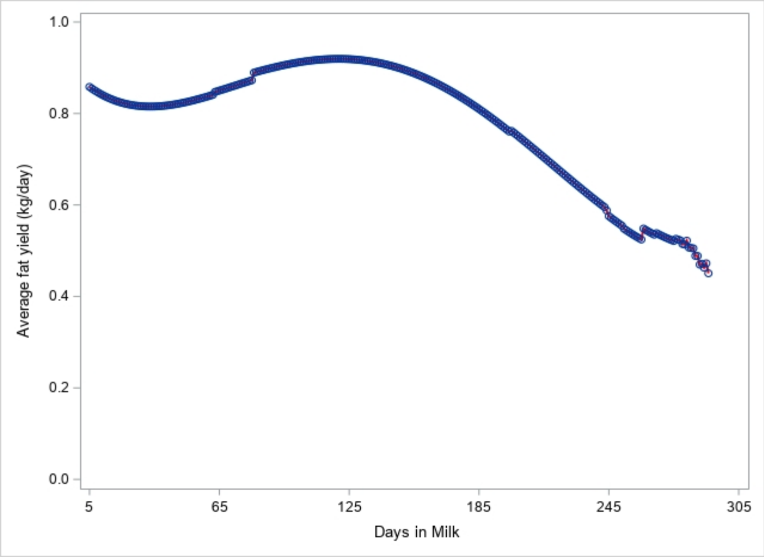

Figure 12: Average fat yield (kg/day) for cows that did not rear a calf (Shed) group from 5 to 305 days in milk (DIM), based on 4th order Legendre mixed model fitted to herd test records.

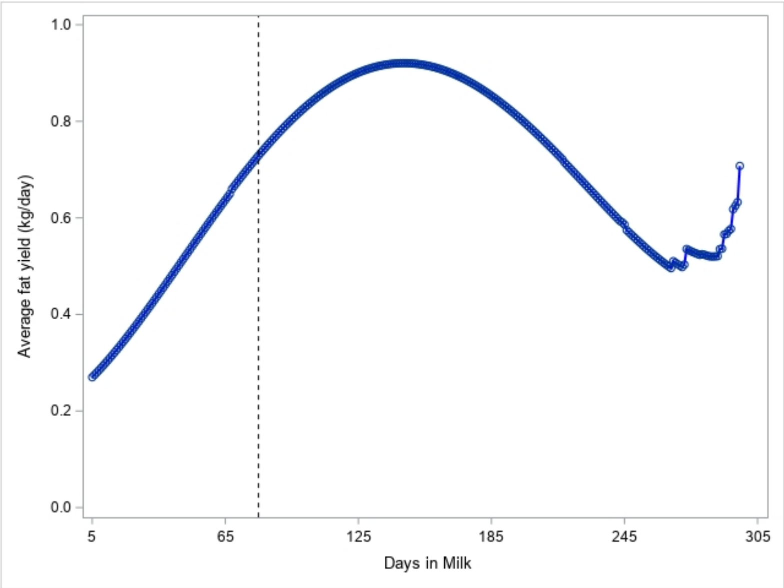

Figure 13: Average fat yield (kg/day) for the cows that reared a calf (Cow) group from 5 to 305 days in milk (DIM), based on 4th order Legendre mixed model fitted to herd test records. The dashed line at DIM 80 marks the industry weaning time.

During the pre-weaning phase, the cows in the Shed group produced ~33 kg more fat than the cows in the Cow group ($P < 0.05$). After weaning, fat yield did not differ significantly between treatments. Across the full lactation period, both groups showed comparable production, although the Shed group produced a numerically greater total fat yield (~17 kg, $P > 0.05$). The comparison of predicted curves (Figure 14) shows clear separation between groups before weaning and convergence after DIM 80, indicating that reduced recorded fat yield in early lactation for the Cow group was limited to the period when calves were suckling.

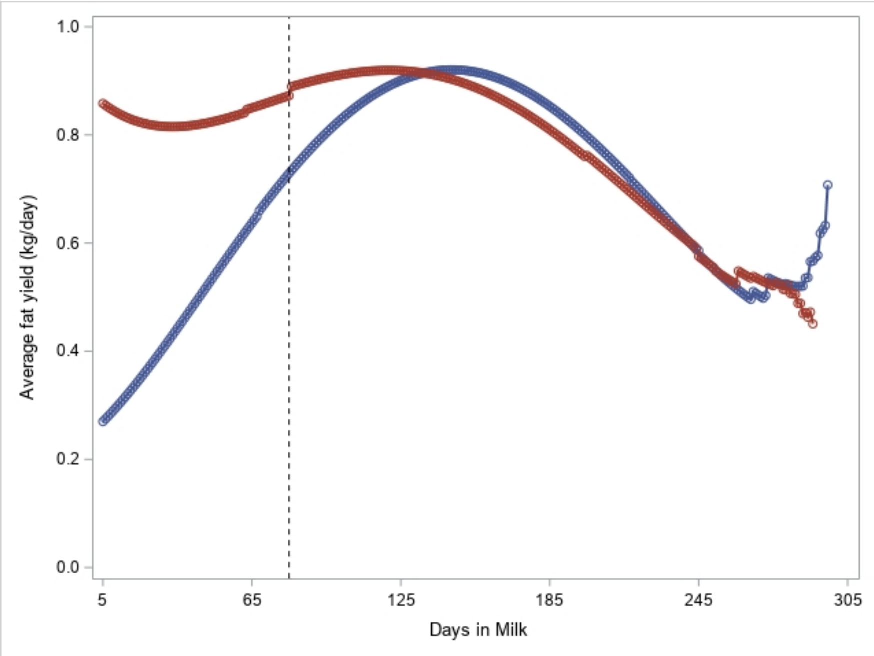

Figure 14: Comparison of average fat yield (kg/day) between cows that reared a calf (Cow (blue)) and cows that did not rear a calf (Shed (red)) groups across 5–305 days in milk (DIM), predicted using a 4th-order Legendre mixed model fitted to herd-test records. The dashed line at DIM 80 marks the industry weaning.

4.1.3 Protein Yield

The cows in the Shed group produced 157.3 kg of protein across the full lactation (Table 5). Approximately 30% of this was produced during early lactation (DIM 5–80), and 70% during mid to late lactation (DIM 81–305). The lactation curve showed a smoother pattern, with protein yield peaking at approximately 130–140 DIM, followed by a steady decline through the remainder of lactation (Figure 15).

The cows in the Cow group produced 139.5 kg of protein across the lactation (Table 5). Around 18% of this was produced during early lactation (DIM 5 to weaning), and 82% during mid to late lactation (DIM 1-day post-weaning to 305). Protein yield increased sharply after weaning, reaching a peak at approximately 140–150 DIM, before declining through late lactation (Figure 16).

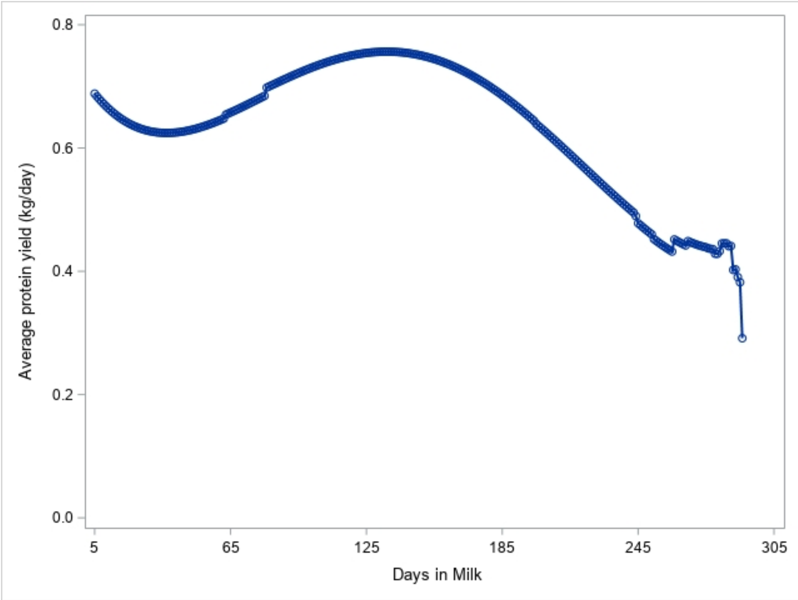

Figure 15: Average protein yield (kg/day) for cows that did not rear a calf (Shed) group from 5 to 305 days in milk (DIM), based on 4th order Legendre mixed model fitted to herd test records.

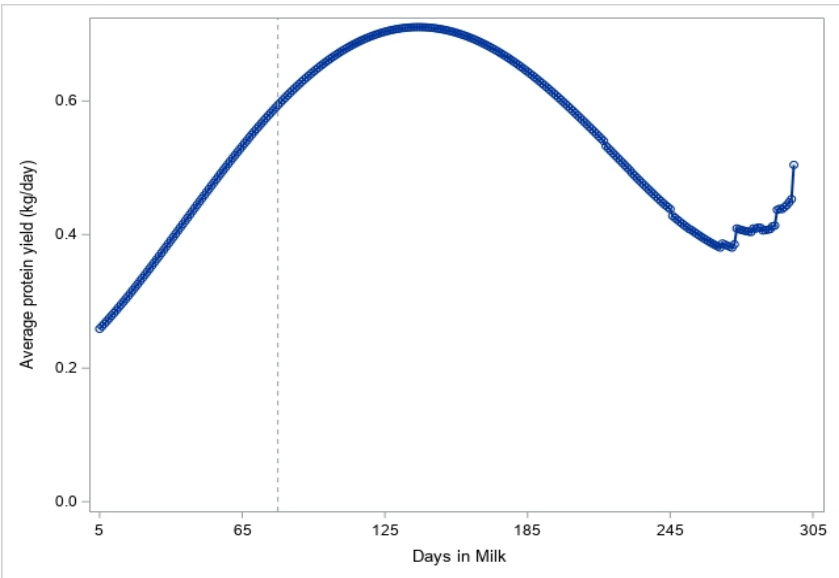

Figure 16: Average protein yield (kg/day) for cows that reared a calf (Cow) group from 5 to 305 days in milk (DIM) based on 4th order Legendre mixed model fitted to herd test records. The dashed line at DIM 80 marks the industry weaning time.

During the pre-weaning phase, the Shed group produced ~23 kg more protein than the Cow group, and this difference was significant. After weaning, protein yield did not differ significantly between groups, with both groups showing broadly similar production. Over the full lactation, the Shed group produced 18 kg more protein than the Cow group, but this difference was not significant. The comparison of predicted curves (Figure 17) shows clear separation between treatments in early lactation due to calf suckling in the Cow group, followed by convergence after DIM 80. This indicates that reduced recorded protein yield in early lactation for the Cow group did not lead to a deficit in total protein yield across the full lactation.

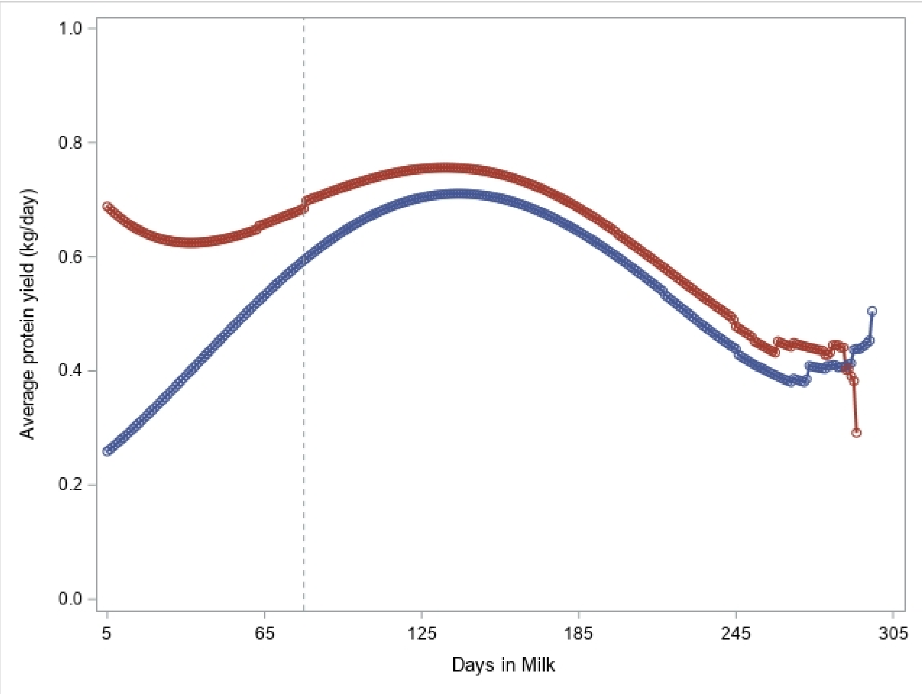

Figure 17: Comparison of average protein yield (kg/day) between cows that reared a calf (Cow (blue)) and cows that did not rear a calf (Shed (red)) groups across 5–305 days in milk (DIM), predicted using a 4th-order Legendre mixed model fitted to herd-test records. The dashed line at DIM 80 marks the industry weaning.

4.1.4 Milksolids Yield

The cows in the Shed group produced 350.4 kg of milksolids across the lactation (Table 5). Approximately 31% of this production occurred during early lactation (DIM 5–80), and 69% during mid to late lactation (DIM 81–305). The lactation curve showed a smooth trajectory, peaking early in lactation and declining steadily thereafter (Figure 18).

The cows in the Cow group produced 316.5 kg of milksolids across the full lactation (Table 5). Around 17% of this was produced during early lactation (DIM 5 to weaning), and 83% was produced after weaning (DIM 1-day post-weaning to 305). The curve increased sharply after weaning, reaching a peak at approximately 140–150 DIM, followed by a typical late-lactation decline (Figure 19).

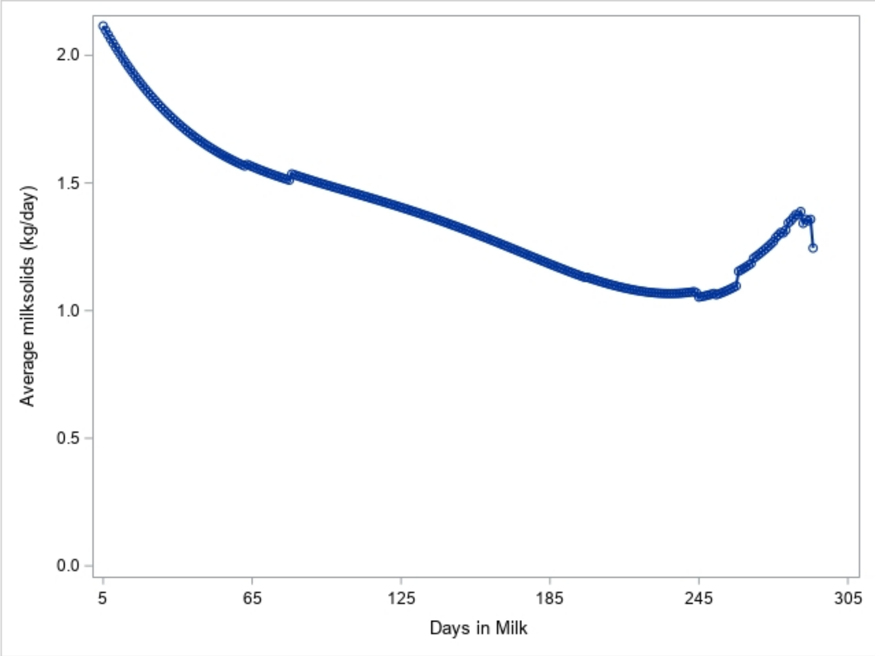

Figure 18: Average milksolids yield (kg/day) for cows that did not rear a calf (Shed) group from 5 to 305 days in milk (DIM), based on 4th order Legendre mixed model fitted to herd test records.

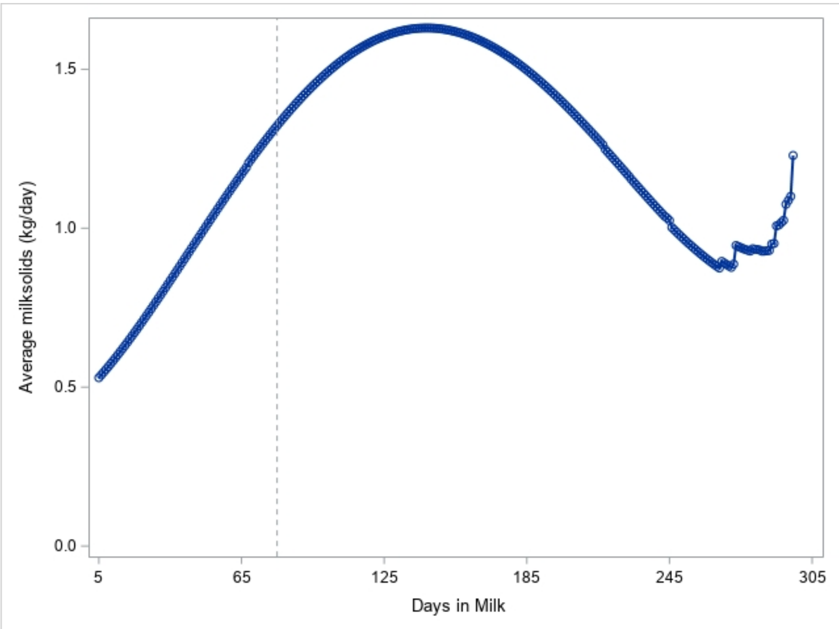

Figure 19: Average milksolids yield (kg/day) for cows that reared a calf (Cow) group from 5 to 305 days in milk (DIM), based on 4th order Legendre mixed model fitted to herd test records. The dashed line at DIM 80 marks the industry weaning time.

During the pre-weaning period, the Shed group produced ~56 kg more milksolids than the Cow group, and this difference was significant. After weaning, milksolids yield did not differ significantly between groups; both groups showed broadly similar post-weaning production. Across the full lactation, the Shed group produced ~34 kg more milksolids than the Cow group, but this difference was not significant. The comparison of predicted curves (Figure 20) shows clear separation between groups during early lactation, reflecting the portion of milk solids consumed directly by calves in the Cow group. After DIM 80, the trajectories converged, demonstrating that cows rearing a calf largely compensated post-weaning and produced total milksolids similar to those of Shed cows over the full lactation.

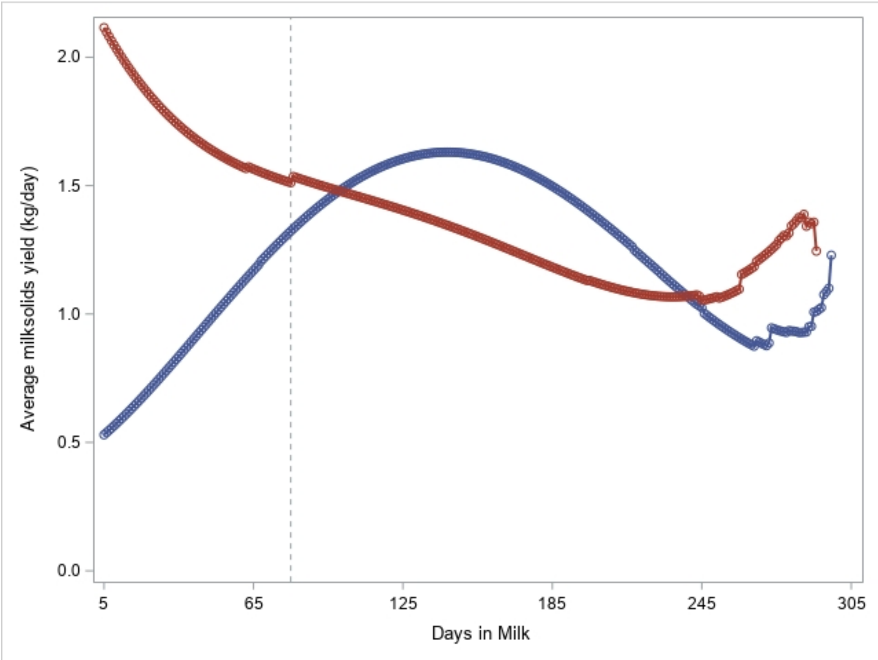

Figure 20: Comparison of average milksolids yield (kg/day) between cows that reared a calf (Cow (blue)) and cows that did not rear a calf (Shed (red)) groups across 5–305 days in milk (DIM), predicted using a 4th-order Legendre mixed model fitted to herd-test records.

4.2 Composition of Milk

Across the full lactation and within each phase, fat and protein concentrations did not differ between groups (Treatment effect, $p > 0.05$; Table 6). There were differences in composition between the pre- and post-weaning (Phase effect, $P < 0.001$), reflecting that cows produced milk with a greater concentration of fat and protein during the post-weaning phase, compared to pre-weaning within each treatment. There was also a significant Treatment x Phase interaction ($P=0.034$) for fat content, indicating that the Cow group produced milk with 1.46% lower fat content pre-weaning compared with post-weaning ($P < 0.0001$). The difference was small (0.47%) in the Shed group, so the concentrations were not statistically significant between the phases. The interactions were also present across treatment groups and phases: the Shed group had 1.10% more fat post-weaning than the Cow group pre-weaning ($P = 0.011$), and the Cow group had 0.83% more fat post-weaning than the Shed group pre-weaning ($P = 0.046$).

Table 6: Fat and protein composition (in percentage, as LS-means ± SE) across the pre-weaning, post-weaning, and total lactation, for cows allocated to the two rearing treatment groups: Shed = cows that had their calves reared artificially and Cow = cows that nursed their calves.

Trait	Period	Cow (LS-means ± SE)	Shed (LS-means ± SE)	P-value
Fat	Pre	4.37 ± 0.29	5.00 ± 0.29	0.1298
	Post	5.83 ± 0.29	5.47 ± 0.30	0.3905
	Total	5.46 ± 0.18	5.29 ± 0.18	0.5261
Protein	Pre	3.65 ± 0.14	3.90 ± 0.14	0.2435
	Post	4.49 ± 0.14	4.48 ± 0.15	0.9952
	Total	4.27 ± 0.09	4.26 ± 0.09	0.9390

Note: Total lactation period covered from 5 days in milk (DIM) to the maximum DIM for both groups. For comparison purposes, lactation was divided as follows: the Shed group pre-weaning from 5 to 80 DIM and post-weaning from 81 DIM to maximum DIM; the Cow group pre-weaning from 5 DIM to weaning and post-weaning from day 1 post-weaning to maximum DIM.

5. Discussion

Cows that reared their calf (the Cow group) produced less saleable kilograms of milk, fat, protein, and therefore, fewer milksolids than those cows that did not rear a calf (the Shed group), supporting the first hypothesis set out to investigate. The difference of 489 kg of milk between the groups was assumed to be consumed by calves being reared by the cows, equating to an estimated intake of 6–8 kg of milk per calf per day prior to weaning (68 ± 15 days). Comparable studies have reported greater values for milk intake from calves reared by cows, but the animals, management systems, and weaning protocols were different from those in the present study. For example, Ospina Rios et al. (2023) found that calves in a half-day contact OAD system in Australia consumed approximately 9.9 litres (10.2 kg) per day by weaning at 10 weeks of age. Likewise, Bryant et al. (2024) reported that under a New Zealand OAD system with partial dam contact (15 hours a day), suckling crossbred (HF x J) calves consumed an estimated ~706 litres (727 kg) of milk over the pre-weaning period of 55 days, equivalent to 12–13 kg per day, and their dams were initially milked OAD before switching to TAD. On the other hand, Mac et al. (2022) in a TAD milking system in Australia, reported intakes up to ~20 kg per day by weaning at 100 days of age, in calves with unrestricted access to their dam. These differences are likely caused by variation in milking frequency, cow-calf contact duration, weaning age, breed or type of calf, and the timepoints used, with additional variation attributable to differences in dam yield potential and genetic merit (Sneddon et al., 2016). Despite numeric differences, all studies agree that natural suckling (the Cow group) substantially reduces saleable milk during early lactation.

The Cow group in this study may have been producing more milk than what was estimated, due to oxytocin release from frequent calf suckling (De Passillé et al., 2008). Frequent suckling provides strong tactile stimulation of the teat, which normally triggers the release of oxytocin and contraction of myoepithelial cells (Bruckmaier, 2001). When machine milking follows a recent suckling bout, circulating oxytocin levels may already be declining, leading to incomplete milk ejection and greater residual milk (Bar-Pelled et al., 1995). This mechanism has likely contributed to the lower recorded yield in the Cow group, in addition to direct removal of milk by calves. However, it is uncertain how much extra milk would have resulted from this additional stimulation and whether it might have increased total daily secretion beyond what was captured at OAD milking. Thus, while the Cow group produced more milk volume than the meter data indicated, the exact volume consumed by calves could not be measured directly and remained uncertain. Several methods, such as the weigh-suckle-weigh technique (Fraga et al., 2018), isotope-dilution (Holleman et al., 1975), or marker-based approaches (Guinguina et al., 2019), have been used to estimate milk intake by calves in research herds. Future research, therefore, warrants direct measurements of milk intake by individual calves to quantify the actual volume of milk transferred to calves and to determine how this relates to the volume of milk harvested at milking, and whether frequent suckling by calves has an actual effect on the dam's milk production.

The Cow group reached peak milk yield later and maintained production longer than the Shed group, indicating greater persistency and supporting the third hypothesis of the study (Bar-

Pelled et al., 1995; Bryant et al., 2024). In general, both groups followed a typical lactation trajectory, characterised by a gradual decline from peak yield. Both Cow and Shed groups in the present study exhibited a substantially delayed peak (~ 100-120 days) compared with the 30 DIM peaks reported by Lembeye et al. (2016) and Jiang et al. (2020), and 50 DIM peak for the first lactation cows reported by Sneddon et al. (2016a) under OAD milking in New Zealand. These differences likely reflect several interacting factors, including parity, breed, OAD milking from calving, and calf suckling effects. All cows in the present study calved within a compact July–August period, so milk yield closely followed the seasonal rise and decline of pasture growth, peaking in November–December (Figure 2) rather than in early lactation. The delayed peak in the Cow group likely reflected both the diversion of milk to calves during early lactation and the stimulatory effect of repeated suckling on mammary secretory activity (De Passillé et al., 2008). Comparable patterns of postponed peak yield and extended persistency have been reported in other cow–calf contact systems (van Knegsel et al., 2022). It is possible that there was also a breed effect for peak and persistency. Lembeye et al. (2016) observed that Jersey cows exhibited the greatest persistency for fat yield, while HF × J cows had the highest persistency for milk and protein yields under OAD milking, indicating that breed differences in curve shape and persistency likely contributed to the variation observed in the present study. However, the low number of animals of each breed within the Cow and Shed groups did not justify this analysis.

The same pattern seen for milk yield was evident for fat, protein, and milksolids yield, which were all significantly lower in the Cow group during the pre-weaning phase, and was consistent with the results from Bryant et al. (2024). This supported the fourth hypothesis of the study, reflecting the unrecorded transfer of milk to the calves while suckling, so the reduction in component yield mirrored the overall decrease in milk harvested. After weaning, however, component yields converged between the groups, indicating that early reduction in harvested fat, protein, and milksolids did not persist into later lactation.

In terms of milk composition (fat and protein %), the present study found that fat concentration differed markedly between pre- and post-weaning phases, with higher fat concentrations observed after weaning across both treatment groups. Although fat concentration was numerically lower during the pre-weaning phase in cows rearing calves, treatment differences within phase were not statistically significant. A significant Treatment x Phase interaction for fat percentage indicates that the magnitude of change in fat concentration from pre- to post-weaning differed between the Cow and Shed groups, with a larger increase observed in the Cow group post-weaning. The numerically lower fat concentration observed during pre-weaning in the Cow group is biologically consistent with milk removal by calves prior to milking. This reduction might be caused by the natural milk production cycle. Particularly in OAD milking, milk accumulates in the udder overnight, and the fat level increases in the cow's udder (Forsbäck et al., 2010). As a result, the uppermost or first portion of milk is rich in fat. Calves reared by their dams likely consumed this fat-rich portion of milk during the morning before milking, leaving a lower-fat residual portion to be harvested with the machine milking. This physiological explanation is consistent with the concentration and distribution effect described by Nicolao et al. (2022), which demonstrated that calves suckling before milking could lower measured fat concentration, whereas suckling after milking increased it because residual hind-milk is richer in fat. The observed non-significant difference in fat concentration is in agreement with the study by Johanssen et al. (2024), who also reported no difference in fat concentration between cow–calf contact and early separation system in pasture-based dairy cows. In contrast, Barth (2020) and Bryant et al. (2024) reported lower fat concentrations in the milk of the cow-reared group.

Protein concentration also did not differ significantly between groups, indicating that calf suckling did not alter the composition of milk across lactation. This agrees with Bryant et al. (2024) and Johanssen et al. (2024) who also reported no treatment effect on the concentration of protein, but in contrast to those of Barth (2020), who reported greater protein concentration. Thus, management factors such as timing of separation, milking time relative to suckling, the completeness of machine milking, milking frequency, breed, and yield potential likely contributed to inconsistent effects on fat and protein concentrations across studies. A detailed investigation is deemed essential to examine the factors that affect the concentration of fat and protein during natural suckling.

Following weaning, cumulative milk and milksolids yields of the Cow group converged rapidly in comparison with the cows from the Shed group, supporting the second hypothesis of the study. This result highlighted that, despite the lower recorded yield during the pre-weaning period, cows that reared their calves were able to compensate after weaning and produced a total post-weaning yield comparable to cows whose calves were reared artificially. This result agrees with studies reporting no post-weaning milk yield losses (Bar-Pelled et al., 1995; Barth, 2020). However, lower full-lactation yields have occasionally been observed when cows were separated near peak yield, likely due to incomplete milk ejection and residual milk accumulation (Bar-Pelled et al., 1995; Barth, 2020; Bryant et al., 2024). For example, Bryant et al. (2024) noted an approximate 1048 litres (1079 kg) reduction in milk when cows were separated near peak production, attributing this to incomplete milk ejection and residual milk effects. Fat and protein concentrations were similar between groups after weaning, with both groups producing milk with higher fat and protein concentrations than pre-weaning.

In the present study, cows were separated before peak lactation and milked once daily, a protocol that might have minimised residual milk, maintained consistent oxytocin release, and prevented a carry-over effect. Management factors such as timing of separation, milking frequency, and completeness of milking might be critical in determining whether extended suckling affects whole season milksolids output. Consistent with this, no statistically significant differences were observed in cumulative post weaning or full lactation milk or milksolids yields between the Shed and Cow groups. Although small numerical differences were present, these were biologically minor and unlikely to be of practical importance, particularly when considered alongside the labour, infrastructure, and milk-feeding costs associated with artificial calf-rearing. For example, across the full lactation, the numeric cumulative milksolids yield was 33.9 kg more per cow in the Shed group. At a milksolids payout of approximately $9 per kg (8.50–9.50 $/kg, midpoint 9.00 $/kg), this equates to about $305 per cow (Fonterra Co-operative Group Ltd., 2025). This potential return would be insufficient to cover the direct costs of artificial calf-rearing, as two 20 kg bags of calf milk replacer alone typically exceed $300 without accounting for additional costs such as labour, feeding equipment, housing, utilities, and health management. Although carrying out an economic assessment of the two rearing practices was not an objective of the study, our observation would indicate that, from a whole-system perspective, the small numerical advantage in harvested milksolids observed in the Shed group is unlikely to compensate for the direct and indirect costs of artificial rearing.

6. Conclusion

This study assessed how different rearing systems (natural suckling in the Cow group or artificial rearing in the Shed group) affected milk, fat, protein, milksolids yields, composition, and the persistency of the lactation curve across a full lactation period in a seasonal, pasture-based, OAD milking herd in New Zealand. Cows rearing their calves produced lower recorded kilograms of milk, fat, protein, and milksolids during early lactation, reflecting milk consumed directly by calves; but yields later converged during post-weaning, and overall yields did not differ between the rearing systems. Additionally, the lactation curve of the Cow group showed a delayed peak and greater persistency compared to the Shed group, which peaked earlier and showed a rapid decline. Fat concentration differed between pre- and post-weaning phases, with a greater post-weaning increase in cows rearing calves, while no treatment differences were detected within phase. Protein concentration did not vary between groups. These results indicate that a managed cow-calf contact system primarily alters early-lactation dynamics without reducing full-season milk or component yields under an OAD milking regime.

Future research should focus on quantifying the actual milk suckled by calves under cow-calf contact systems and evaluating associated physiological factors, such as oxytocin release, milk ejection efficiency, and residual milk volume. These measures would provide direct evidence of how suckling influences actual milk transfer and secretion dynamics. Long-term investigations across successive lactations are necessary to determine whether cow-calf contact affects udder health, reproductive performance, or whole-season milksolids output, and to assess any implications for overall farm profitability. Incorporating economic analyses of labour and infrastructure requirements, as well as following calves reared under the natural and artificial systems in the long-term, would further clarify the costs and benefits associated with each rearing method, thereby providing dairy farmers with robust evidence to guide management decisions.

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