



Invited review: Nutritional and management factors that influence colostrum production and composition in dairy cows

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ABSTRACT

Colostrum is a rich source of nutritional and non-nutritional components and is recognized as essential to transfer passive immunity to newborn calves. Because of the individual and seasonal variability in colostrum yield and composition, maintaining an adequate supply of high-quality colostrum year-round remains a challenge for commercial dairy producers. In this narrative review, we described the individual, seasonal, and herd-level variability of colostrum production and summarized the association between individual animal factors such as parity, sex of the calf, calf birth weight, as well as indicators of the cow's metabolic status and the yield and composition of colostrum. Further, we reviewed the current knowledge on the influence of prepartum nutrition and management strategies on colostrum production. Research on the metabolizable energy and protein supplied in the prepartum diet as well as on the inclusion and source of vitamins, minerals, and feed additives suggests prepartum nutrition influences the yield, quality, and composition of colostrum. Furthermore, the prepartum environment and dry period length remain influential factors in the production of colostrum. However, additional research is needed to understand the mechanisms by which prepartum nutrition and management affect colostrum production. Finally, time from calving to colostrum harvest and oxytocin administration as well as the current knowledge on the effect of heat treatment and colostrum storage strategies on colostrum components were discussed. To conclude, we identify critical gaps in knowledge for future focus of investigation in colostrum research.

Key words: colostrum, nutrition, management, immunoglobulin G, colostrogenesis

INTRODUCTION

Mounting evidence supports the importance of colostrum for raising healthy calves (Lombard et al., 2020;

Abuelo et al., 2021; Crannell and Abuelo, 2023; Sutter et al., 2023). Because the cotyledonary synepitheliochorial bovine placenta inhibits transfer of maternal antibodies into fetal circulation, newborn dairy calves rely on timely ingestion of high-quality colostrum with low bacterial contamination to transfer passive immunity (TPI) as well as for nutrients and other bioactive components (Fischer-Tlustos et al., 2021b; Lopez and Heinrichs, 2022). Poor TPI in calves has been associated with lower ADG, a greater risk for preweaning morbidity and mortality, and a lower likelihood to reach first insemination and calving (Crannell and Abuelo, 2023; Sutter et al., 2023). Further, colostrum intake aids in the development of the gastrointestinal tract (Hammon et al., 2013; Malmuthuge et al., 2015; Hammon et al., 2020; Pyo et al., 2020) and has been shown to positively affect first-lactation milk production (Faber et al., 2005; Abuelo et al., 2021). As such, it is recommended to feed calves 8.5% to 10% of BW (Conneely et al., 2014; Godden et al., 2019) of high-quality (≥ 50 g of IgG/L; $\geq 22.0\%$ Brix) colostrum with low bacterial contamination (total plate count $< 100,000$ cfu/mL; fecal coliforms $< 10,000$ cfu/mL; McGuirk and Collins, 2004) at birth. A growing number of producers have also implemented an extended colostrum (Kehoe et al., 2007; Robbers et al., 2021a; Westhoff et al., 2023b) or transition milk feeding program to promote preweaning health, growth, and development (Conneely et al., 2014; Kargar et al., 2020; Pyo et al., 2020; Van Soest et al., 2020; Abuelo et al., 2021) as well as sell colostrum for production of commercial products (Costa et al., 2023; Westhoff et al., 2023b). Thus, an adequate supply of high-quality colostrum is a critical component for the viability of commercial dairy farms.

Research on the epidemiology of colostrum production has exposed the individual and seasonal variability (Gavin et al., 2018; Borchardt et al., 2022; Westhoff et al., 2023b) and prompted investigations to discover animal, environmental, nutritional, and managerial factors that influence the yield as well as IgG and component concentrations of colostrum. Further, dairy producers put forth equipment and labor resources required to harvest, store, reduce contamination, and feed high-quality

Received October 25, 2023.

Accepted December 19, 2023.

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The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-24. Nonstandard abbreviations are available in the Notes.

colostrum. As such, this narrative review will describe the variability in colostrum production, discuss prepartum nutritional and management strategies as well as postharvest practices associated with the production of colostrum and the preservation of colostrum components, and identify knowledge gaps to direct future focus of investigation. The key words “colostrum” and “cow” as well as other relevant key words were used to identify literature that pertained to each variable discussed in this narrative review. Additional references were identified through citation mining. Unless otherwise stated, we refer to colostrum as the first milking only and to data from Holstein dairy cattle.

VARIABILITY IN COLOSTRUM PRODUCTION

Seasonality

Of interest, colostrum yield (Karl and Staufenbiel, 2016; Gavin et al., 2018; Borchardt et al., 2022), Brix % or IgG concentration (Zarei et al., 2017; Borchardt et al., 2022), and composition (Zarei et al., 2017; Soufleri et al., 2021) exhibit seasonality. Colostrum yield was greatest in June (6.6 kg) and decreased to its lowest average yield of 1.3 kg in December in multiparous Jersey cows from a single dairy located in Texas (Gavin et al., 2018). Colostrum yield from primiparous Jersey cows also showed seasonality (June: 6.5 kg; December: 4.2 kg), albeit less than multiparous cows (Gavin et al., 2018). In a study conducted in Germany, average colostrum yield from primiparous Holstein cows was greatest in April (4.1 ± 0.3 kg) and lowest during November (3.2 ± 0.3 kg), and average colostrum yield from multiparous cows peaked in May (5.5 ± 0.3 kg) and was lowest in October (3.8 ± 0.3 kg), respectively (Borchardt et al., 2022). Conversely, authors in the United States have associated calving during the summer (June–August) with reduced colostrum IgG concentration (Morin et al., 2001; Rossi et al., 2023). Seasonality was also observed for other colostrum components in samples collected in Northern Greece with greatest concentrations of fat in the spring (March–May), protein in the fall (September–November) and winter (December–February), and lactose in the fall, winter, and spring (Soufleri et al., 2021), and these associations might be related to changes in light as well as temperature and humidity exposure (discussed below). Although the inverse seasonal relationship between yield and IgG concentration has been hypothesized to be influenced by IgG dilution (Pritchett et al., 1991; Guy et al., 1994; Kehoe et al., 2011), reductions in yield (1 kg) or increased colostrum DM (1%) were associated with marginal increases in IgG concentration (<3 g of IgG/L; Conneely et al., 2013; Mann et al., 2016).

Individual Variability

It is known that colostrum yield and composition from dairy cows has high individual variation (Kehoe et al., 2007; Baumrucker and Bruckmaier, 2014; Dunn et al., 2017; Borelli et al., 2022). Colostrum yield averaged (range) 4.3 (0–26.5) kg from Jersey (Gavin et al., 2018) and 4.0 to 6.1 (0.0–43.8) kg from Holstein cows (Borchardt et al., 2022; Rossi et al., 2023; Westhoff et al., 2023b), respectively, with an intraherd coefficient of variation of 25% to 74% (Soufleri et al., 2021). Yet, when considering the amount of colostrum needed to feed a calf 2 colostrum meals (e.g., 3–4 L at first feeding; 2 L at second feeding), 60.0% and 65.3% of Holstein cows failed to produce ≥ 6 L of first-milking colostrum (Rossi et al., 2023; Westhoff et al., 2023b). Similarly, colostrum Brix % and IgG concentrations averaged (range) 23.8% to 27.6% (7.0%–58.0%; Biemann et al., 2010; Quigley et al., 2013; Gavin et al., 2018; Borchardt et al., 2022; Westhoff et al., 2023b) and 45.0 to 118.7 g/L (1.4–261.2 g/L; Gulliksen et al., 2008; Quigley et al., 2013; Dunn et al., 2017; Shivley et al., 2018; Kessler et al., 2020a; Rossi et al., 2023), respectively. Using the current industry standard for high-quality colostrum (IgG ≥ 50 g/L; Brix % $\geq 22.0\%$), Buczinski and Vandeweerd (2016) and Westhoff et al. (2023b) reported that 7.7% to 32.7% and 21.5%, respectively, of cows produced poor-quality colostrum. In addition, important nutritional components for the calf including colostrum fat {mean (SD) [quartile 1, quartile 3]; 6.4 (3.3) [2.5, 10.9] %}, protein {17.8 (4.0) [12.7, 22.7] %}, and lactose {2.15 (0.73) [1.2, 3.1] %} vary by cow (Soufleri et al., 2021), resulting in an inconsistent nutritional value.

Researchers investigating factors that affect colostrum yield and quality have mostly used observational data to uncover individual animal factors such as parity (Conneely et al., 2013; Dunn et al., 2017; Fischer-Tlustos et al., 2020; Westhoff et al., 2023b), breed (Muller and Ellinger, 1981; Guy et al., 1994; Zarcu et al., 2010; Kessler et al., 2020a), and month of calving (Dunn et al., 2017; Zarei et al., 2017; Soufleri et al., 2021; Rossi et al., 2023) that commonly arise as associated with colostrum production. Within common dairy breeds, Jersey cows produced colostrum with the highest quality but experienced periods of low colostrum supply specifically during the fall and winter months (Muller and Ellinger, 1981; Gavin et al., 2018). Multiparous cows produced a greater volume of colostrum with higher IgG as well as protein concentrations while fat concentration was lower compared with primiparous cows (Karl and Staufenbiel, 2016; Dunn et al., 2017; Soufleri et al., 2021; Westhoff et al., 2023b). Other variables from selected studies such as characteristics of the previous lactation or calf as well as

the heritability of colostrum production are summarized in Table 1. Recently, authors have associated carrying a heifer calf as well as having a stillbirth with a lower colostrum yield in both Holstein and Jersey cattle (Karl and Staufenbiel, 2016; Gavin et al., 2018; Borchardt et al., 2022; Westhoff et al., 2023b) and these associations might be influenced by calf birth weight (Conneely et al., 2013; Sutter et al., 2019). Circulating concentrations of placental lactogen during gestation have been positively associated with calf birth weight and milk production in the subsequent lactation (Bolander et al., 1976, Hayden et al., 1979; Patel et al., 1996), and circulating progesterone and estrogen among other hormones have been reviewed for their effect on mammary development (Erb, 1977). We hypothesize that endocrine signals during late gestation might contribute to the association between calf related variables (sex, birth weight, and stillbirth) and colostrum yield.

Other variables such as gestation length, previous lactation length, and milk yield in the current or previous lactation resulted in mixed associations with colostrum production (Kessler et al., 2014; Cabral et al., 2016; Gavin et al., 2018; Kessler et al., 2020b; Poindexter, 2021; Borchardt et al., 2022; Westhoff et al., 2023b) and might be the result of differences in data collection, statistical analysis, or indicate the lack of a cause-effect relationship. Colostrum quality and composition appear to have low to moderate heritability (Soufleri et al., 2019; Costa et al., 2021a) and low colostrum yield has been linked to Holstein and Jersey sire lines (Karl and Staufenbiel, 2016; Gavin et al., 2018). However, the feasibility and extent to which genetic selection might improve colostrum production warrants further investigation.

An emerging area of study has considered the effect of the dam's metabolism on colostrum production. In an observational study, Poindexter (2021) observed a positive association between colostrum yield and hypocalcemia at 1 DIM. Further, it was recently revealed that production of ≥ 6 L of colostrum was associated with an elevated prepartum BHB concentration and antioxidant potential as well as a lower cholesterol concentration and oxidant status index in Holstein dairy cows (Rossi et al., 2023). Elevated colostral IgG concentration or Brix % was associated with higher prepartum serum albumin and glucose concentrations as well as a lower calcium concentration, glutamate dehydrogenase activity, and urinary net acid base excretion (Immler et al., 2021; Rossi et al., 2023). Concentrations of circulating fatty acids as well as BHB at 0, 1, and 7 DIM were positively associated with colostrum yield (Karl and Staufenbiel, 2016), and for every 1-L increase in colostrum yield above the mean of 5.43 L, cows had a 1.1 (1.0–1.1) greater odds of hyperketonemia when evaluated between 7 and 14 DIM (Vanholder et al., 2015). Further, a 10.1% to 15.0% prevalence of

hyperketonemia, at the herd level, during the early postpartum period (3–14 DIM) was associated with a greater colostrum yield (Westhoff et al., 2023a). Although these data are suggestive of a relationship between maternal metabolism and colostrum production in Holstein dairy cattle, the causality as well as the interactions between management, nutrition, and metabolism in respect to colostrogenesis remain unknown.

Herd-Level Variability

Herd-level differences in colostrum yield and composition within a geographic region (Costa et al., 2021b; Rossi et al., 2023; Westhoff et al., 2023b) suggest variables beyond season of calving and individual animal factors influence colostrum synthesis. Annual median (quartile 1, quartile 3) colostrum yield and mean (SD) Brix % ranged from 3.7 (2.6, 5.3) kg to 7.7 (6.0, 8.6) kg and 22.0% (2.7%) to 28.4% (5.1%) on 18 Holstein dairy farms (Westhoff et al., 2023b). Although less than the intraherd variability, interherd coefficient of variation was 35% for colostrum yield and between 6% and 22% for colostrum components (Soufleri et al., 2021) suggesting farm management, prepartum nutrition, or environmental conditions influence colostrum synthesis. Recent insights into the influence of dry period management (Grusenmeyer et al., 2006; Mayasari et al., 2015; Borchardt et al., 2022; Westhoff et al., 2023b) and prepartum nutrition (Martinez et al., 2018; Swartz et al., 2022; Hare et al., 2023; Westhoff et al., 2023a), emphasize the potential to alter colostrum synthesis. However, because of the individuality and seasonality of colostrum production as well as the lack of complete knowledge on the metabolic and endocrine signals that regulate colostrum synthesis (Baumrucker et al., 2021, 2023), our ability to explain the aforementioned differences in colostrum yield or composition have been largely limited to date. As such, our success in the ability to employ on-farm managerial and nutritional strategies to improve colostrum yield and composition has been minimal thus far and highlights the need for mechanistic studies to fill this important knowledge gap.

PREPARTUM NUTRITIONAL AND MANAGEMENT STRATEGIES

Prepartum Nutrition

Prepartum nutritional strategies are often evaluated by their effect on postpartum health and productivity. However, with the growing interest in and utility for colostrum (Lopez and Heinrichs, 2022; Costa et al., 2023), researchers have recently started to simultaneously evaluate the effect of these nutritional strategies

Table 1. Previous lactation and calf characteristics as well as heritability associated with colostrum yield and quality

Reference	Variable	Yield ¹	Quality ¹
Kessler et al., 2014	305-d cumulative milk yield	Not associated	—
Cabral et al., 2016	Previous lactation milk yield	Not associated	↑
Dunn et al., 2017	Previous lactation 305-d milk yield	—	↑
Kessler et al., 2020b	Previous lactation 305-d milk yield	Not associated	↑
Poindexter, 2021	Milk yield for first 70 DIM	↑	—
Borchardt et al., 2022	Previous lactation 305-d milk yield	↑	↓
Westhoff et al., 2023b	Previous lactation 305ME, kg		
	≤13,090	Referent	Referent
	13,091–15,862	↑	ND
	>15,862	↑	↓
Cabral et al., 2016	Previous lactation length	Not associated	↑
Gavin et al., 2018	Previous lactation length	↑	Not associated
Westhoff et al., 2023b	Previous lactation length, d		Not associated
	≤297	Referent	
	297–344	ND	
	>344	↑	
Kessler et al., 2020b	Gestation length	Not associated	↓
Borchardt et al., 2022	Gestation length ²	Not associated	Not associated
	Short		
	Normal		
	Long		
Westhoff et al., 2023b	Gestation length ³		
	Short	Referent	Referent
	Normal	↑	ND
	Long	↑	ND
Angulo et al., 2015	Calf sex		
	Female	Referent	Referent
	Male	↓	↑
Gavin et al., 2018	Calf sex		
	Twins	Referent	Referent
	Female	↓	↑
	Male	ND	↑
Kessler et al., 2020b	Calf sex	Not associated	Not associated
Poindexter, 2021	Calf sex		—
	Female	Referent	
	Male	↑	
	Twins	↑	
Borchardt et al., 2022	Calf sex		Not associated
	Female	Referent	
	Male	↑	
	Twins	↑	
Westhoff et al., 2023b	Calf sex		
	Female	Referent	Referent
	Male	↑	↑
	Twins	↑	ND
Karl and Staufenbiel, 2016, 2017	Stillbirth		
	Alive	Referent	Referent
	Dead	↓	↓
Borchardt et al., 2022	Stillbirth		Not associated
	Alive	Referent	
	Dead	↓	
Westhoff et al., 2023b	Stillbirth		
	Alive	Referent	Referent
	Dead	↓	↓
Conneely et al., 2013	Calf birth weight	↑	Not associated
Karl and Staufenbiel, 2016, 2017	Calf birth weight	↑	Not associated
Kessler et al., 2020b	Calf birth weight	Not associated	↓
Soufleri et al., 2019	Heritability	Not associated	↑
Costa et al., 2021b	Heritability	—	↑

¹Arrows indicate a positive or negative association with the variable relative to the referent when the variable was categorized. Not associated = $P > 0.05$; ND = no difference from referent group ($P > 0.05$); — = not reported. 305ME = 305-d mature equivalent milk production; quality = IgG concentration or Brix %.

²Short = 257–269 d, normal = 270–280 d, long = 281–293 d.

³Short = 263–273 d, normal = 274–282 d, long = 283–293 d.

on colostrum production. We encourage consideration of colostrum outcomes in these types of studies as future meta-analyses can be conducted to provide clarification of effect sizes and directions where there is currently no consensus.

Dietary Energy. For a comprehensive review of the current knowledge on the effect of prepartum intake of carbohydrates, fat, and protein on colostrum production, we direct the reader to Hare et al. (2023). In brief, altering starch concentrations to increase the energy density of the prepartum diets does not appear to alter colostrum yield (Mann et al., 2016; Richards et al., 2020; Vasquez et al., 2021) but resulted in a lower colostrum IgG concentration and higher insulin concentration as well as altered fatty acid composition (Mann et al., 2016; Fischer-Tlustos et al., 2021a). Inclusion of fat in the prepartum diet did not affect yield or component concentrations of colostrum and the effect of fat supplementation on IgG concentration remains mixed (Garcia et al., 2014; Salehi et al., 2016; Jolazadeh et al., 2019; Daneshvar et al., 2020; Sun et al., 2022; Sun et al., 2023).

Dietary Protein. Colostrum yield from multiparous cows did not differ when feeding 744 or 976 and 849, 1,200, or 1,387 g of estimated MP/d (Amirabadi Farahani et al., 2017, 2019). In a study with 2 levels of MP (65 vs. 90 g/kg DM) and 2 levels of DMI, Akhtar et al. (2022) did not observe an effect of MP level, DMI, or the interaction on colostrum yield, IgG, or component concentrations. Similarly, the level of CP fed prepartum (Santos et al., 2001; Toghyani and Moharrery, 2015) or inclusion of rumen-protected lysine (Fehlberg et al., 2020) did not affect colostrum composition. However, we recently observed a tendency for an interaction between MP level fed prepartum and parity group such that cows entering parity 2 tended to produce more colostrum (9.4 ± 0.9 vs. 7.2 ± 0.9 kg) when fed an elevated level of MP (1,606 vs. 1,180 g of estimated MP/d) but colostrum yield from parity ≥ 3 cows was not affected by MP supply (5.1 ± 1.0 vs. 6.4 ± 1.0 kg; Westhoff et al., 2024), respectively. Further, increasing the MP supply during the far-off (1,203 vs. 846 g of estimated MP/d) and close-up (1,631 vs. 1,258 g of estimated MP/d) periods resulted in a treatment \times parity interaction for IgG concentration such that cows entering parity 2 fed an elevated MP supply had a greater IgG concentration (61.3 ± 2.3 vs. 55.2 ± 2.8 g/L) compared with parity 2 cows fed a lower MP supply, but MP supply did not affect IgG concentration in parity ≥ 3 cows (58.4 ± 3.0 vs. 56.8 ± 2.9 g/L; Van Hese et al., 2023), respectively. Although nulliparous heifers were not included in the 2 aforementioned studies, it remains plausible that younger cows might benefit from an additional MP supply to support mammary epithelial cell turnover during the dry period; however, the mechanism responsible as well as the validity of the interaction of

treatment and parity remain uncertain. Because of limited data as well as the aforementioned interaction, the effect of prepartum MP supply on colostrum production should be further investigated with inclusion of nulliparous heifers.

Hypocalcemia Prevention Strategies. Prepartum dietary strategies to mitigate hypocalcemia, including feeding a zeolite or manipulating the DCAD, alter prepartum DMI and circulating mineral concentrations (Kerwin et al., 2019; Santos et al., 2019). Because of the metabolic demand of colostrum synthesis (Goff and Horst, 1997), disruptions in prepartum mineral metabolism or nutrient intake have potential to interfere with colostrogenesis. When feeding a diet including a zeolite at 500 g/d, colostrum yield (5.8 ± 0.8 vs. 7.3 ± 0.8 kg) and IgG concentrations (83.4 ± 4.8 vs. 76.3 ± 4.8 g/L) did not differ in the treatment compared with the control diet that did not contain zeolite, respectively (Kerwin et al., 2019). Further, colostrum fat, protein, and lactose concentrations were not affected by a zeolite fed at 150 or 300 g/d (Marin et al., 2020). Apart from an elevated IgG concentration from cows fed a negative (-22 mEq/100 g) compared with a neutral (-3 mEq/100 g) DCAD diet described by Diehl et al. (2018), altering the prepartum DCAD (Lopera et al., 2018; Martinez et al., 2018; Zimpel et al., 2021) or prepartum DCAD and dietary calcium concentration (Glosson et al., 2020; Rajaeerad et al., 2020; Graef et al., 2021) did not affect colostrum IgG concentration or Brix %. Although most authors did not observe an effect on colostrum yield (Weich et al., 2013; Diehl et al., 2018; Martinez et al., 2018; Glosson et al., 2020; Rajaeerad et al., 2020; Zimpel et al., 2021), feeding diets with a more severe negative DCAD has been associated with reduced colostrum yield (Lopera et al., 2018; Westhoff et al., 2023a). Although the reduction in yield was hypothesized to be affected by a lower DMI (Lopera et al., 2018), the complexity of calcium homeostasis, including the effect of 25-hydroxyvitamin D₃ (discussed below), the role of the different widely used dietary hypocalcemia prevention strategies, and serotonin's negative association with colostrum yield (Hernández-Castellano et al., 2017; Kessler et al., 2018), deserve further attention.

Mineral and Vitamin Inclusion. Recent evidence suggests the source of dietary vitamin D influences colostrum synthesis. Martinez et al. (2018) observed that feeding 3 mg of calcidiol (25-hydroxyvitamin D₃) tended to increase colostrum yield (7.8 ± 0.8 vs. 6.0 ± 0.8 kg) compared with cows fed cholecalciferol (vitamin D₃), respectively. Further, when fed in combination with a positive DCAD diet, calcidiol also tended to increase concentrations of fat, protein, and TS; however, feeding calcidiol did not result in altered colostrum fat, protein, or TS concentrations when cows were fed a diet with a

negative DCAD (Martinez et al., 2018). Additional data supported a trend for increased colostrum yield without an effect on colostrum components when cows were fed negative DCAD diets and cholecalciferol was replaced with calcidiol at either 1 or 3 mg/d (Poindexter et al., 2023) and when 0.625 mg/d cholecalciferol was replaced with 3 mg/d calcidiol (Silva et al., 2022). Although it remains unclear how calcidiol affected colostrum yield, Martinez et al. (2018) hypothesized calcidiol might have direct effects on epithelial cell proliferation through hormonal control or calcium and substrate availability. Colostrum IgG concentration was not affected by source of vitamin D in a study by Poindexter et al. (2023) in contrast to Martinez et al. (2018). Further, source of vitamin D did not affect yield or composition of transition milk, collected as the second milking after calving (Poindexter et al., 2023). Because of the interaction between DCAD and source of vitamin D on colostrum components and the inconsistent results on IgG concentration when replacing cholecalciferol with calcidiol, further research is needed to determine the mechanism of action as well as increase the external validity of previous findings.

In addition to vitamin D, researchers have explored the source and inclusion of dietary minerals and vitamins on colostrum production. Because of limited placental transfer, certain colostrum mineral and vitamin concentrations have also been considered as an important source for the newborn calf (Quigley and Drewry, 1998; Przybylska et al., 2007). Apart from a greater IgG concentration reported by Kincaid and Socha (2004) and Formigoni et al. (2011), replacing inorganic with organic trace minerals did not affect colostrum yield, IgG, or component concentrations (Karkoodi et al., 2012; Roshanzamir et al., 2020; Kerwin et al., 2023; Ogilvie et al., 2023). Further, colostrum mineral concentrations did not differ when replacing 50% of inorganic Cu, Mn, and Zn with organic protein sources (Formigoni et al., 2011); however, inclusion of selenized yeast or selenium biofortified alfalfa increased Se concentrations in colostrum from Jersey and Holstein cows (Weiss and Hogan, 2005; Jaaf et al., 2020; Ogilvie et al., 2023). Although dietary supplementation of 0.2 mg/kg Se with 70 IU/kg of diet DM vitamin E in combination with an injection of 50 mg of Se and 300 IU of vitamin E at 21 d before expected calving increased colostrum concentrations of α -tocopherol (Weiss et al., 1990), dietary supplementation alone does not appear to be an effective strategy to increase colostrum α -tocopherol concentrations (Weiss et al., 1992). Similarly, maternal supplementation of 700 to 800 mg/d β -carotene did not affect colostrum yield or concentrations of IgG, retinol, α -tocopherol, or components and yielded mixed results on colostrum β -carotene concentrations (Aragona et al., 2021; Prom et al., 2022). Supplemental B vitamins, including nicotinic acid, increased colostrum IgG con-

centration (Aragona et al., 2016, 2020), whereas biotin altered fatty acid composition in colostrum (Duplessis et al., 2022).

Feed Additives. A limited number of feed additives have been investigated for their effect on colostrum production and results have largely been mixed or inconsistent. Inclusion of magnesium butyrate supplemented at 105 g/d increased colostrum yield and total IgG mass but IgG concentration and colostrum components were not affected (Kovács et al., 2023). Feeding monensin at 24.2 g/t of total dietary DM did not affect colostrum yield or IgG concentrations (Vasquez et al., 2021). Further, supplementing prepartum cows with 13.6 and 20.4 g/d of choline ions did not affect Brix % or component concentrations but Swartz et al. (2022) reported a 2.9 ± 0.8 and 2.5 ± 0.8 kg increase in yield, respectively. In another study where cows were supplemented with 0, 15, or 22 g/d of choline ions, colostrum yield was only different in the 15 g/d group, showing an increase from 3.4 (2.2–5.1) kg in control to 4.4 (2.8–6.7) kg or 5.4 (3.5–7.9) kg in cows fed 15 g/d of 2 choline products, respectively (Holdorf et al., 2023). In contrast to the aforementioned studies, Zenobi et al. (2018) and Bollatti et al. (2020) did not observe an effect on colostrum yield when supplementing 12.9 g/d of choline ions. Moreover, in a field study consisting of 21 prepartum pens ($n = 2,171$ cows), colostrum yield as well as IgG and component concentrations were not affected by choline supplementation at 12.9 g/d (Poindexter, 2021). Including mannan oligosaccharides (Franklin et al., 2005; Westland et al., 2017) or direct-fed microbials and enzymes (Ort et al., 2018; Real, 2022) in the prepartum diet has yielded mixed results on colostrum production. Contrary to Franklin et al. (2005) and Ort et al. (2018), colostrum yield was increased by supplementing 2 g/d of *Saccharomyces cerevisiae*-derived mannan oligosaccharides (Westland et al., 2017) or 5 g/d of direct-fed microbials and enzymes (Real, 2022). The influence of feed additives and supplementation requires further consideration and replication of studies before conclusions can be drawn for on-farm use.

Prepartum Management

Prepartum Environment. The seasonality of colostrum production, as described above, is confounded by changes in environmental conditions including exposure to light as well as heat exposure, measured as temperature-humidity index (THI). Authors have associated THI or photoperiod with colostrum yield (Cabral et al., 2016; Gavin et al., 2018; Borelli et al., 2022; Westhoff et al., 2023b), IgG concentrations or Brix % (Cabral et al., 2016; Shivley et al., 2018; Zentrich et al., 2019), and colostrum composition (Nardone et al., 1997; Román et al., 2021; Alward, 2023). When THI 7 d before calving and

light intensity 14 d before calving were categorized, colostrum yield from multiparous Holstein cows increased as THI and light intensity categories increased (Westhoff et al., 2023b). Gavin et al. (2018) reported a positive correlation between colostrum yield from Jersey cows and photoperiod as well as maximum weekly THI. Nevertheless, the lack of studies manipulating photoperiod and THI independent of one another in controlled settings makes it challenging to determine if a causal relationship exists. In a study by Alward (2023), colostrum yield, Brix %, and IgG concentration from Holstein and Jersey cows did not differ when cows were managed for a short or long-day photoperiod (8 vs. 16 h of light/d). Similarly, increasing photoperiod from 8 to 16 h of light/d for the entire dry period did not affect colostrum yield and IgG concentration (Morin et al., 2010). Although more data are needed to determine if increased light exposure during the dry period can affect colostrum production, short day light exposure (8 h/d) during the dry period remains the optimal lighting program during the dry period for the resulting benefits in lactation performance (Auchtung et al., 2005; Velasco et al., 2008).

Regarding the effect of heat stress, heat abatement strategies appear to influence colostrum production (Nardone et al., 1997; Karimi et al., 2015). In a study by Seyed Almoosavi et al. (2021), cooled cows (access to shade, sprinklers, and fans) produced more colostrum (7.1 ± 0.6 kg) with an elevated IgG concentration (92.2 ± 2.5 g/L) compared with heat-stressed cows (access to shade but not to sprinklers or fans; 4.0 ± 0.6 kg; 74.7 ± 2.5 g/L). In addition, compared with the cooled cows, colostrum yield (6.0 ± 0.6 kg) and IgG concentration (88.5 ± 2.5 g/L) did not differ in a third group of cows that were cooled but offered the same amount of feed as the heat-stressed group (Seyed Almoosavi et al., 2021). As has been shown with milk production (Baumgard and Rhoads, 2013), reduced feed intake only partially explains a lower colostrum yield as a result of heat stress in the aforementioned study and provides further support for thermal management of dry cows beyond the positive effects on cow and calf productivity (Tao and Dahl, 2013; Laporta et al., 2017; Laporta et al., 2020).

Dry Period Length. Observational data suggest that decreasing the length of the dry period results in a lower colostrum yield (Poindexter, 2021; Soufleri et al., 2021; Borelli et al., 2022). In a study on 12,553 Holstein cows from 18 dairy farms, Westhoff et al. (2023b) reported an increase in colostrum yield as the length of the dry period, categorized as <47, 47 to 67, or >67 d, increased. Jersey cows with a 45-d dry period had a 1.7 times greater odds of producing <2.7 kg of colostrum compared with cows with a 65-d dry period. Further, researchers revealed a 60-d dry period resulted in $+2.2 \pm 0.4$ and $+2.6 \pm 0.6$ kg more colostrum compared with cows managed for

a shortened (30–40 d) dry period (Grusenmeyer et al., 2006; Mayasari et al., 2015). Colostrum IgG concentration was not affected by a dry period shortened to 35 to 40 d (Grusenmeyer et al., 2006; Cermakova et al., 2014; Shoshani et al., 2014), but was reduced ~30% to 59% in the absence of a dry period compared with a shortened dry period (Rastani et al., 2005; Klusmeyer et al., 2009; Mayasari et al., 2015). Additionally, a dry period ≥ 85 d was associated with greater concentrations of colostrum fat, but protein concentration was not affected by dry period length (Soufleri et al., 2021).

Time in the Close-Up Pen. Because colostrum synthesis exerts a metabolic demand during late gestation, parturition diet formulation (discussed above) as well as length of exposure to the close-up ration has been evaluated in 2-phase dry-cow systems. Contrary to Weich et al. (2013), Lopera et al. (2018), and Sørensen (2020), Amirabadi Farahani et al. (2017) observed a trend for a 2.0 ± 0.8 kg greater colostrum yield with a 21-d compared with a 10-d close-up period. The aforementioned increase in yield was larger than that observed in an observational study (10 d = 4.9 ± 0.2 kg vs. 20 d = 5.2 ± 0.1 kg; Borchardt et al., 2022). Yet, when categorized as ≤ 15 , 16 to 30, or >30 d, time in the close-up pen was not associated with colostrum yield or Brix % in an analysis of 16,032 Holstein cows (Westhoff et al., 2023b). Pen stocking density ranging from 41% to 163% was not associated with colostrum yield in an observational analysis of 238 cows (Borelli et al., 2022). Further, decreasing stocking density (100% headlock, 109% stalls vs. 80% headlock, 86.3% stalls, Silva et al., 2016; and 120% vs. 100% vs. 80% headlock and stalls, Jiang et al., 2021) of the close-up pen did not affect colostrum yield or Brix percentage. Although it appears that total dry period length is more influential for colostrum synthesis compared with time and stocking density of the close-up pen, recent evidence suggests that the interaction of pen move with dry-cow booster vaccinations to increase specific calf-health related antibodies in colostrum should also be considered. Cows administered booster vaccinations at 28 d relative to calving and moved to the close-up pen at 21 d relative to calving had greater colostrum IgG concentration (160.4 ± 7.0 g/L) compared with cows vaccinated and moved at 21 d relative to calving (134.4 ± 7.0 g/L) but neither treatment differed from cows vaccinated and moved to the close-up pen at 28 d relative to calving (148.3 ± 7.2 g/L; Menichetti et al., 2021). Although replication of these data are lacking, results of this study suggest that vaccination 1 wk earlier and not coinciding with potential detrimental effects of a pen move was more beneficial than earlier vaccination in combination with a pen move. When timing of vaccination is considered independent of pen moves, administration of vaccines earlier in the dry period or given repeatedly, and consistent with manu-

facturer label recommendations, might offer a management strategy to increase vaccine derived antibodies in colostrum because most colostral immunoglobulins are produced in and transferred from maternal circulation.

Dry-Off Procedure and Udder Health. Selective and blanket dry-cow therapy protocols are commonly used to reduce intramammary infection (Zwald et al., 2004; Winder et al., 2019), but limited data are available on their effect on colostrum production. In studies using a teat sealant only or an antibiotic in addition to a teat sealant on cows with a low risk (SCC <200,000 cells/mL) for intramammary infection, Lavery et al. (2022) and Vasquez et al. (2022) found no differences in colostrum fat, protein, lactose, and IgG concentrations as well as the colostrum microbiome. However, the effect of dry-cow therapy might depend on the risk of intramammary infections as the yield of colostrum from a persistently infected gland, defined as growth of ≥ 50 cfu/mL of the respective mastitis-causing pathogen when sampled 14 and 7 d relative to calving, was reduced compared with noninfected glands (Maunsell et al., 1998). Although clinical mastitis in the previous lactation was not associated with colostrum yield, Brix %, or IgG concentrations (Aghakhani et al., 2022) and IgG, IgM, and IgA as well as fat, protein, and lactose concentration were not affected by intramammary infection (Maunsell et al., 1998; Enger et al., 2021; Pikhtirova et al., 2022), maintaining udder health during the dry period should remain a priority independent of considerations for colostrum production.

HARVESTING COLOSTRUM

Time to Colostrum Harvest

The time near parturition marks the transition from lactogenesis I, including colostrum synthesis, to copious milk production (lactogenesis II; Baumrucker and Bruckmaier, 2014). Concentrations of most colostral components and bioactive factors (fat, protein, TS, SCC, immunoglobulins, oligosaccharides, miRNA, insulin, IGF-1, minerals, vitamins, and others) decrease in subsequent hours to days following parturition while milk yield and lactose concentrations increase (Foley and Otterby, 1978; Blum and Hammon, 2000; Hammon et al., 2000; Fahey et al., 2020; Wilms et al., 2022). As such, timely colostrum harvest has been recommended. Quigley et al. (2013) observed a quadratic relationship between IgG concentration and time from calving to colostrum harvest such that IgG concentration was lower when collected ≥ 8 h postcalving. In agreement, other authors have observed decreased colostrum Brix % or IgG concentration in colostrum harvested ≥ 6 to 9 h postcalving and an increased colostrum yield when harvested ≥ 12 h postcalving (Conneely et al., 2013; Silva-Del-Río et al., 2017; Soufleri et

al., 2021). To maximize colostral components and IgG concentration, we recommend harvesting colostrum <8 h following calving. Notably, producers that feed a calf its dam's colostrum should prioritize colostrum harvest ≤ 2 h from calving to ensure timely ingestion of colostrum for the newborn calf.

Administration of Oxytocin

As with milk letdown, release of oxytocin from the pituitary gland is a necessary response for a complete colostrum harvest and is most often achieved by tactile teat stimulation (Bruckmaier and Blum, 1998). Therefore, disruptions in oxytocin release, as has been reported in primiparous cows and cows milked in unfamiliar locations (Bruckmaier et al., 1992, 1993) might prevent a complete removal of colostrum. Contrary to the study hypothesis, Sutter et al. (2019) found that colostrum yield was not affected when the calf was present before and during colostrum harvest or when administering 20 IU of oxytocin intramuscularly 3 min before manual stimulation in preparation for colostrum harvest, but IgG concentration was increased by 5.3 ± 2.6 and 6.3 ± 2.7 g/L, respectively. Elevated oxytocin concentrations can alter the tight junctions of the mammary gland (Allen, 1990; Wall et al., 2016; Farmer et al., 2017) which might have affected IgG concentration in the above-mentioned study, leading to the small observed increase in IgG concentration. Oxytocin injections have not been associated with changes in fat, protein, or lactose concentrations in milk (Nostrand et al., 1991; Ballou et al., 1993) although the effect of oxytocin administration or presence of the calf on other colostral components has not been reported to the knowledge of the authors. Given findings reported by Sutter et al. (2019) originated from a single commercial dairy farm, the external validity on these data remain uncertain, and create a need for additional studies on multiple dairy farms with varying widely used premilking routines. Further, research is needed to determine whether oxytocin administration at colostrum harvest affects the milk letdown reflex at subsequent milkings.

POSTHARVEST COLOSTRUM MANAGEMENT

On-Farm Assessment of Colostrum Quality

Assays to determine colostral IgG (radial immunodiffusion [RID], ELISA, and turbidimetric immune assay [TIA]) are time consuming and costly, making them infeasible for commercial dairy producers. Moreover, because of a bias between ELISA and TIA when compared with RID (Gelsinger et al., 2015b; Dunn et al., 2018; Breuer et al., 2023; Röder et al., 2023), comparing results between methods is not recommended. However, determining the

specific gravity or refractive index of colostrum via a hydrometer and Brix refractometer, respectively, have been investigated for their role as rapid and affordable indirect estimates of colostrum quality. When compared with IgG determined by RID, a hydrometer and Brix refractometer exhibited a moderate to strong correlation (hydrometer: $r = 0.58$ to 0.79 ; Brix refractometer: $r = 0.64$ to 0.75 ; Biemann et al., 2010; Quigley et al., 2013; Bartier et al., 2015; Morrill et al., 2015; Röder et al., 2023). Of note, colostrum temperature as well as composition can affect the specific gravity of colostrum (Mechor et al., 1992; Morin et al., 2001). Using a cut-point of $\geq 22.0\%$, a meta-analysis revealed the posttest probability of an IgG concentration ≥ 50.0 g/L was 94.3% (95% CI: 90.7%–96.9%; Buczinski and Vandeweerd, 2016). For the hydrometer, the negative predictive value (probability of a hydrometer result to correctly identify a sample as ≥ 50.0 g of IgG/L) with a cut-point of 1,047 was 97.1 (95% CI: 92.8%–99.2%; Röder et al., 2023) suggesting both hydrometers and Brix refractometers offer suitable indirect estimates to identify high-quality colostrum for on-farm use. In a study by Godden and Hazel (2011), colostrum collected at the beginning of the milking process resulted in a higher IgG concentration compared with a composite sample and to samples collected during the milking process. Collection of a composite sample from the bucket after the milking process is recommended for quality assessment (Robbers et al., 2021b). Although high-quality colostrum is currently defined as an IgG concentration ≥ 50 g/L, recommended IgG intake through colostrum might change as our understanding of the short-term and long-term benefits of achieving higher concentrations of IgG in the calf rather than merely surpassing a minimum threshold grows (Lombard et al., 2020).

Bacterial and Pathogen Contamination

Along with preserving the nutritional and bioactive components, minimizing contamination is fundamental to successful colostrum management. Feeding contaminated colostrum can reduce absorption of immunoglobulins (James et al., 1981; Elizondo-Salazar and Heinrichs, 2009a) as well as expose calves to pathogenic microorganisms (Streeter et al., 1995; Godden et al., 2006). However, minimizing bacterial contamination and pathogen transfer via colostrum remains an area of opportunity. In an evaluation of 1,241 colostrum samples from 39 Czech farms, only 352 (28.4%) and 1,095 (88.2%) samples were below the industry standard total plate count ($<100,000$ cfu/mL; McGuirk and Collins, 2004) and total coliform count ($<10,000$ cfu/mL; McGuirk and Collins, 2004), respectively (Šlosárková et al., 2021). Further, Morrill et al. (2012) noted that 409 of 746 (54.8%) colostrum samples from 67 farms in the United

States were below the industry standard total plate count. As we further understand the effects that bacterial and pathogen contamination have on the calf, industry standard thresholds for total plate and coliform counts among other contaminants might arise or need to be reevaluated (Mann et al., 2020b; Morin et al., 2021). Although some pathogens can be shed in the mammary gland, significant pathogen and environmental contamination occur particularly during harvest but also during storage or feeding of colostrum (Stewart et al., 2005). In fact, of the 155 cultured colostrum samples, 21 (13.5%) samples were positive for a gram-positive mastitis agent while 117 (75.5%), 127 (81.9%), and 128 (82.6%) samples resulted in environmental, fecal, and skin and mucosa contaminants, respectively (Šlosárková et al., 2021). As such, special consideration should be given to identify the risk of pathogen shedding in the mammary gland as well as minimize fecal and environmental contamination (Streeter et al., 1995; Stabel, 2001). In addition, cleaning and sanitizing all equipment that comes in contact with the colostrum (Renaud et al., 2017; Buczinski et al., 2022) as well as rapidly cooling colostrum after harvest and properly treating and storing colostrum can aid in reducing bacterial replication and preserving the nutritional and bioactive components.

Heat Treatment

Heat treatment can be an effective strategy to decrease total bacterial counts in colostrum with minimal effect on IgG concentration when treated at 60°C for 60 min. (Godden et al., 2006; Elizondo-Salazar et al., 2010; Donahue et al., 2012; Hesami et al., 2020; Malik et al., 2022). In a recent meta-analysis, the loss of IgG when colostrum was heat treated at $\leq 60^\circ\text{C}$ and $>60^\circ\text{C}$ to 63°C was -3.6 (-7.3 to 0.1) and -21.7 (-27.3 to -16.1) g/L, respectively (Rabaza et al., 2023). Further, in a study by Kryzer et al. (2015), batch heat treatment resulted in a lower total plate count but a higher total coliform count when compared with single bag heat treatment. Notably, neither batch nor bag heat treatment result in a sterile product and some bacterial species, such as staphylococci and environmental streptococci, appear more tolerant to survive treatment (Elizondo-Salazar et al., 2010; Mann et al., 2020a). In a study by Godden et al. (2006), heat treating colostrum at 60°C for 60 min. was successful in eliminating inoculated viable infectious agents *Mycoplasma bovis* (10^8 cfu/mL), *Listeria monocytogenes* (10^6 cfu/mL), *Escherichia coli* (10^6 cfu/mL), and *Salmonella enteritidis* (10^6 cfu/mL), but *Mycobacterium avium* subspecies *paratuberculosis*, the agent causing Johne's disease, inoculated at 10^3 cfu/mL was recovered in 1 of 4 batches of colostrum. Further, *Staphylococcus aureus* and coliforms were not detected after heat treating colos-

trum at 60°C for 60 min (Elizondo-Salazar et al., 2010). The effectiveness of heat treatment to eliminate viable bacteria in colostrum depends on the initial pathogen load (Mann et al., 2020a). As such, preventing contamination during colostrum harvest and storage should remain a priority regardless of the use of heat treatment. Additionally, heat treatment of colostrum alone was not effective at decreasing the risk of *Mycobacterium avium* subspecies *paratuberculosis* transmission (Godden et al., 2015). Because colostrum only accounts for one potential source of pathogen exposure, measures should be taken to identify and control other routes of disease transmission concurrently.

Although heat treatment is an effective strategy to reduce bacterial counts, recent evidence suggests it also alters other colostrum components. When inoculating sterile colostrum with fecal *E. coli*, we observed a greater bacterial growth from 4 to 24 h in heat-treated compared with raw or frozen colostrum (A. M. McKane, T. A. Westhoff, and S. Mann, College of Veterinary Medicine, Cornell University, Ithaca, NY, personal communication), suggesting heat treatment decreases the bacteriostatic or bactericidal properties of colostrum. Heat treatment also increased colostrum viscosity (Rabaza et al., 2023), altered the profile of colostrum proteins and metabolites (Tacoma et al., 2017; Mann et al., 2020a; Xu et al., 2021), as well as reduced or eliminated reactive oxygen and nitrogen species (Mann et al., 2023) and active immune components such as colostrum leukocytes and reduced activity of the alternative complement pathway (Chandler et al., 2023).

Further, heat treatment reduced colostrum insulin and IGF-1 concentrations (Mann et al., 2020a), both of which are important for neonatal gastrointestinal tract development (Ontsouka et al., 2016; Hammon et al., 2020; Fischer-Tlustos et al., 2021b), but also has been shown to increase prebiotics such as free oligosaccharides (Fischer et al., 2018). Despite this, feeding colostrum heat treated at $\leq 60^\circ\text{C}$ to calves resulted in a 2.5 to 6.6 g/L increase in circulating IgG concentration and a 3.8% to 11.5% increase in apparent efficacy of IgG absorption (AEA; Elizondo-Salazar and Heinrichs, 2009b; Hesami et al., 2020; Rabaza et al., 2023) as well as a lower risk of preweaning treatment (189 [36.5%] vs. 171 [30.9%]; Godden et al., 2012). However, data from Gelsing et al. (2015a) demonstrated that regardless of heat treatment, calves fed colostrum with a high bacteria count had a 9.5 to 12.2 g/L lower circulating IgG concentration at 48 h and a 18.7% to 19.9% lower AEA, emphasizing the need to minimize bacterial contamination at time of feeding. In addition to proper sanitation, a combination with heat treatment at 60°C for 60 min or use of an approved colostrum additive (reviewed by Denholm, 2022; we urge the reader to verify local regulations for approved colostrum

additives allowed as a feed additive) should be considered as strategies where needed to secure calf health.

Storage

On-farm storage of colostrum is a critical component of a colostrum management system to preserve colostrum composition and IgG concentration as well as to maintain an adequate supply through seasonal declines in yield. Unless fresh colostrum is fed immediately, it should be rapidly cooled before entering storage in the refrigerator (4°C) or freezer (-20°C). Colostrum stored at room temperature had greater bacteria counts by 6 h and 42 times more bacteria by 48 h compared with colostrum stored in the refrigerator (Cummins et al., 2016, 2017). Although storing colostrum in the refrigerator does not alter IgG concentration, bacterial counts continued to increase over time (Cummins et al., 2016). However, use of potassium sorbate as a colostrum preservative in combination with refrigeration has been an effective strategy to reduce bacterial growth for 96 h compared with raw colostrum in the refrigerator (Stewart et al., 2005). Because of this, it is recommended that colostrum is stored in the refrigerator for ≤ 2 d or ≤ 4 d when treated with potassium sorbate (Stewart et al., 2005). For long-term storage, colostrum can be frozen at -20°C (Carlson and Muller, 1977; Schipper et al., 1981). Limited data are available to determine the effect of extended storage time on colostrum components. In a study by Abd El-Fattah et al. (2014), concentrations of IgG and IgM in bovine colostrum were not affected when storing colostrum in a freezer for 3 mo, but IgG and IgM decreased 14.6% and 60.5%, respectively when stored for 6 mo. Notably, IgG (30.2 ± 3.0 g/L) and IgM (3.0 ± 0.1 g/L) concentrations in the aforementioned study were lower than that typically observed. Freezing human colostrum preserved concentrations of epidermal growth factor, transforming growth factor (TGF)- $\beta 2$, tumor necrosis factor (TNF)- α , TNF-receptor I, IL-6, IL-10 for 12 mo; however, IgA, IL-8, and TGF- $\beta 1$ were only stable when frozen for 6 mo (Ramírez-Santana et al., 2012). Notably, ≥ 2 freeze-thaw cycles have been shown to reduce IgG concentration (Morrill et al., 2015) and ≥ 3 freeze-thaw cycles reduced Brix % (Stalker et al., 2023). Therefore, colostrum should be frozen in individual meal portions in a manual defrosting freezer. To avoid raising the internal temperature of the freezer, colostrum bags or containers can be cooled with ice or cold water before entering the freezer and care should be taken to avoid contact between thawed and frozen containers or bags. Colostrum can be thawed/reheated in a water bath at $\leq 60^\circ\text{C}$ (Balthazar et al., 2015) without negative effects on serum IgG concentration in the calf (Holloway et al., 2001; Donovan et al., 2007). Although some authors have not reported

reduced concentrations of IgG when thawing colostrum in a microwave (Jones et al., 1987; Pfeiffer et al., 2010), Balthazar et al. (2015) observed a 20% to 31% loss of IgG. Heating colostrum in the microwave resulted in coagulation likely from uneven heating as well as reduced volume and CP (Jones et al., 1987) and is strongly discouraged. As with heat treatment, exposing colostrum to temperatures $>60^{\circ}\text{C}$ when thawing can lead to reductions in IgG concentration.

Recently, we have shown freezing colostrum short-term increased abundance of microRNA as well as preserved the activity of the alternative complement pathway and bacteriostatic or bactericidal properties compared with raw colostrum (Chandler et al., 2023; A. M. McKane, T. A. Westhoff, and S. Mann, College of Veterinary Medicine, Cornell University, Ithaca, NY, personal communication). Similar preservation of bacteriostatic or bactericidal properties have been reported with breast milk after freezing although the activity may decrease with extended storage (Ogundele, 2000, 2002; Lorico and Perez, 2012). Further, freezing colostrum did not alter odd- or branched-chain fatty acids (Xin et al., 2020), lactoferrin concentrations (Holloway et al., 2003), or antioxidant capacity (Usuga et al., 2022), and was associated with a 1 log reduction in *Mycoplasma bovis* titer (Gille et al., 2018), but viable maternal leukocytes were eliminated after short-term freezing of colostrum (Chandler et al., 2023).

TRANSITION MILK

Because calves suckling their dams would naturally experience a gradual decline in nutrient density as well as bioactive concentrations in milk during the first few days of life (Fischer et al., 2019; Tortadès et al., 2023), feeding transition milk (milkings 2–6) to calves after feeding colostrum has been explored. Feeding transition milk for 1 to 3 d in addition to colostrum resulted in an increased preweaning weight gain (Van Soest et al., 2020) and lower odds of receiving an elevated ear/eye or nasal score (Conneely et al., 2014). Further, calves fed a 1:1 colostrum:whole milk mixture for 3 d after a colostrum meal had increased intestinal surface area as well as increased villi height compared with calves fed whole milk (Pyo et al., 2020). Despite its benefit to the calf, feeding transition milk on a commercial dairy farm presents an added management challenge because of the additional equipment and labor required to harvest and feed transition milk to a select group of calves. Research seeking to determine the optimum duration to feed transition milk, as well as identifying the short- and long-term benefits to health, growth, development, and future productivity of calves, is needed. Further, comparing the outcomes when calves are fed maternal transition milk against protocols

feeding whole milk and against those using colostrum supplements to replace transition milk will be instrumental in adoption of transition milk programs on commercial dairy farms. Transition milk can be harvested from cows 2 to 6 milkings after calving and can be fed fresh, heat treated, or stored as described above for colostrum. Further, transition milk can be pooled from multiple cows; however, measures should be taken to lower the risk of disease transmission when pooling transition milk in the same fashion as when pooling colostrum from multiple dams. Alternatively, mixing colostrum supplements with milk has been used as a substitution for harvesting transition milk (Berge et al., 2009).

FUTURE OPPORTUNITIES

Despite the variables summarized herein, the proportion of variance in colostrum production we have been able to explain remains small, in part, due to the incomplete knowledge of the physiological mechanisms of colostrum formation (Figure 1). Because of the importance of and traditional focus on IgG alone, transfer of IgG into the mammary gland has historically defined colostrogenesis and is believed to begin 3 to 5 wk before calving when IgG concentrations in the mammary gland exceed the concentration in maternal circulation (Brandon et al., 1971; Baumrucker and Bruckmaier, 2014). During the days to weeks leading up to calving, nutritional and non-nutritional components accumulate in the mammary secretion (Hurley, 1987; Bitman et al., 1992; Guy et al., 1994; Baumrucker et al., 2023; Hare, 2023) and numerous hormones (estradiol, progesterone, prolactin, cortisol, leptin, placental lactogen, and others) have been discussed as having a potential role in colostrum formation as well as the initiation of lactogenesis II (reviewed by Barrington et al., 2001; Baumrucker et al., 2021; and Bigler et al., 2023). However, the timing and complete cascade of signals that influence these biological mechanisms, as well as active and passive transfer of constituents remain unknown. Understanding these signals as well as the onset of lactogenesis II are particularly important as the capacity, rate, and time of which colostrum components enter or are synthesized in the mammary gland could influence the osmotic gradient and as such affect yield as well as the concentration of colostrum components.

The ability to improve colostrum production through parturition nutrition and management as well as genetic selection remains a plausible and achievable goal. However, because of the high variability observed in colostrum production and limited available data, future research is needed to discover new interventions that directly influence colostrum yield and composition and increase the external validity of existing findings. Further, inclusion

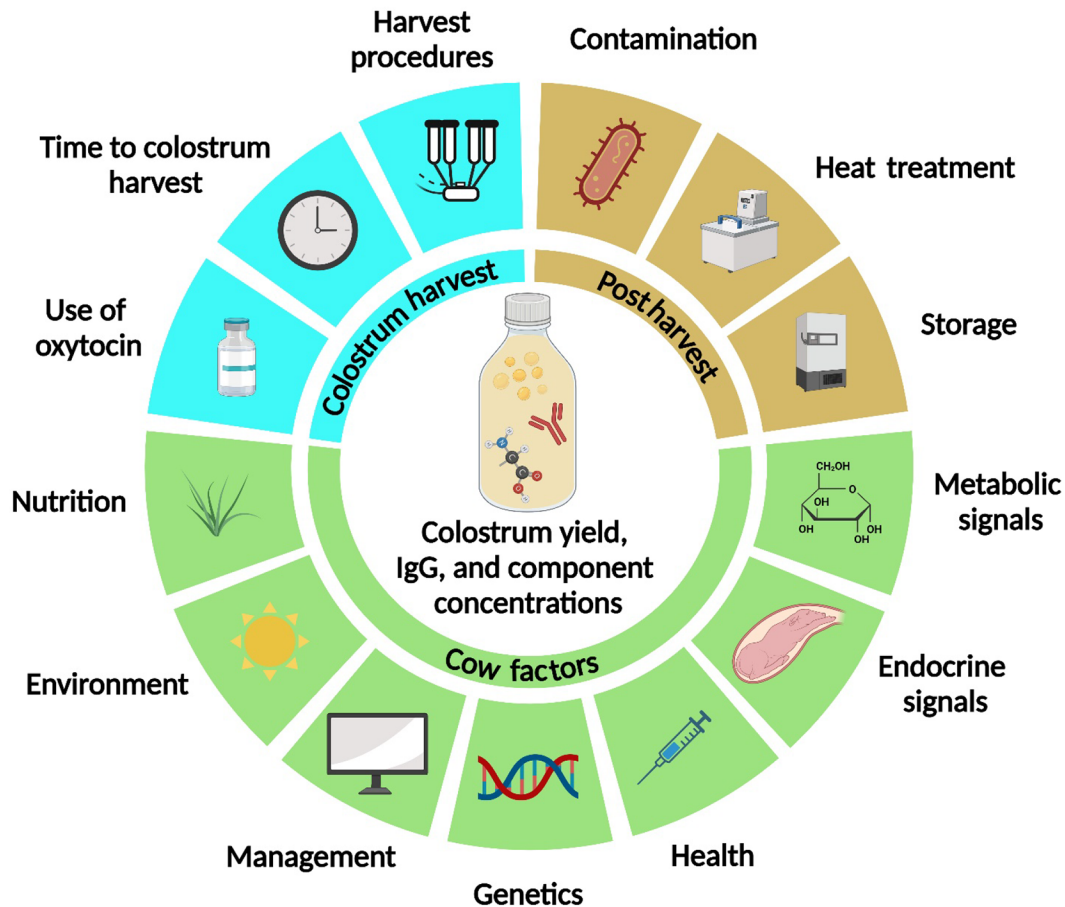


Figure 1. Summary of cow, colostrum harvest, and postharvest variables identified as the focus of future colostrum investigations. Figure was created with BioRender.

of colostrum outcomes and consistent reporting among future transition cow investigations will facilitate subsequent meta-analyses of these typically smaller studies. The mechanisms of how nutritional or management interventions affect colostrum production remains unclear. Attention to the interactions with maternal metabolism and endocrine signals is necessary to understand these regulatory mechanisms.

Finally, data on the role of harvest and postharvest management on colostrum components as well the effect on health, growth, and future productivity of calves fed colostrum are needed. Research investigating whether harvest procedures for colostrum and transition milk should differ from the procedures used to harvest mature milk is limited at this time. Further, recording colostrum yield and Brix % readings into dairy management software on commercial dairy farms will enable high-powered and externally valid observational data analysis to identify risk factors and genomic trends. Recent evidence suggests heat treatment, bacterial contamination, refrigeration, and freezing affect colostrum components or the absorption of IgG in the calf (Ramírez-Santana et

al., 2012; Tacoma et al., 2017; Fischer et al., 2018; Mann et al., 2020a, 2023; Chandler et al., 2023; Stalker et al., 2023). Focusing on the nutritional and developmental role of other colostrum components and how current postharvest management affects these components might redirect best-practice guidelines and redefine colostrum quality. Moreover, there is need for further research into the use of colostrum as a therapeutic as well as into the success of treatment protocols using colostrum (Carter et al., 2021, 2022). Finally, the effect of feeding transition milk as well as practical strategies to harvest and feed transition milk on a commercial farm warrant further investigation.

CONCLUSIONS

Colostrum yield and composition exhibit individual, herd, and seasonal variability. Although multiple animal and environmental variables have been linked with colostrum production, researchers have been mostly unsuccessful in explaining this variability. Parturition nutrition and management as well as the interaction with maternal

metabolism appear to affect colostrum production. However, suitable on-farm strategies to improve colostrum production remain limited, partially because of our incomplete knowledge on the regulatory mechanisms of colostrum formation. Storage of colostrum remains an effective approach to overcome periods of low colostrum supply. Postharvest colostrum management should limit bacterial contamination and future studies need to quantify the effect on colostrum components and ultimately on calf health.

NOTES

This study received no external funding. No human or animal subjects were used, so this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board. The authors have not stated any conflicts of interest.

Abbreviations used: AEA = apparent efficacy of IgG absorption; RID = radial immunodiffusion; THI = temperature-humidity index; TIA = turbidimetric immune assay; TPI = transfer of passive immunity.

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