PHOTOPERIOD AND TEMPERATURE-HUMIDITY INDEX DURING THE DRY PERIOD IMPACT COLOSTRUM AND MILK PRODUCTION IN DAIRY CATTLE

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ACADEMIC ABSTRACT

Colostrum quality is critical to calf health as colostrum provides immunoglobulins (Ig) that are critical for a calf's immune system. Despite close management of factors known to affect colostrum production, 23% of dairy cows are still producing inadequate volume or quality of colostrum, which causes calf death and poor performance. Therefore, the objectives of this dissertation are to investigate factors that affect colostrum production and methods to improve colostrum yield and quality. Based on previous literature showing that photoperiod impacts milk yield post-calving in dry cows and that light intensity and temperature-humidity index (THI) impact colostral Ig content, I hypothesized that photoperiod and THI during the dry period impact colostrum yield and quantity in Holstein and Jersey cows. The first study evaluated the isolated effect of photoperiod on colostrum production. Dry cows were housed in a temperature-controlled barn and exposed to either short-day photoperiod (SDPP) of 8 h of light per day or long-day photoperiod (LDPP) of 16 h of light per day for the entire dry period until calving. Altered photoperiod had no effect on colostrum yield, Ig content or other components of colostrum. However, Jersey cows had a higher Brix score, fat, protein, IgA and IgM. After calving, milk production was not affected by photoperiod treatment, likely due to cows being exposed to an irregular lighting scheme. The second study evaluated the combined effects of photoperiod and THI during the dry period on colostrum production and broke cows into a bottom (1), middle (2) and top (3) third based on their photoperiod exposure. Holstein cows produced more colostrum than Jersey cows in each photoperiod category. For both breeds, photoperiod category 1 cows produced less colostrum than cows in photoperiod category 2 and 3. Brix score did not differ by breed but differed by farm and photoperiod category with farm 1, photoperiod category 3 cows having increased Brix score compared to farm 2, photoperiod category 1 and 2 cows. Colostrum components for Jersey cows did not differ by photoperiod category. However, colostrum volume, Brix score, protein and SNF were all impacted by THI and (or) photoperiod variables in predictive modeling. This indicates that colostrum yield and quality in Holstein and Jersey cows are similarly impacted by both photoperiod exposure and THI exposure during the last two months of pregnancy. Therefore, farmers can utilize short-day photoperiod during the dry period during times of moderate THI to improve milk production post-calving without negatively impacting colostrum production. However, future studies are needed to tease out THI and photoperiod impact on colostrum on a large scale in order to improve dry cow management and colostrum production.

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GENERAL ABSTRACT

Cows do not transfer antibodies or immunoglobulins to their offspring during gestation and calves are born deficient in antibodies that are critical for a healthy immune system. Instead, cows transfer antibodies into the first milk that they produce, termed colostrum. After calves ingest the colostrum, the antibodies are absorbed by the small intestine and enter circulation where they can traverse the body to identify and neutralize pathogens. To ensure adequate immune system function, calves must ingest 150 – 200 g of antibodies within 6 h of birth. However, around 23% of cows do not produce enough antibodies in their colostrum or have low colostrum yield overall. 19% of calves do not ingest enough antibodies and will die or have negative health effects that persist into adulthood as a result.

Therefore, the objective of this dissertation is to investigate methods to improve colostrum production in cows to improve calf health and reduce calf deaths. While several factors that affect colostrum production have been identified and are managed for optimum colostrum production, there is still high variation in colostrum production from cow to cow. Based on previous research showing that colostrum yield varies seasonally and that daily light exposure, or photoperiod, can impact milk production, I hypothesized that photoperiod and temperature-humidity index (THI) during the last two months of pregnancy impact colostrum production in cows.

The first study was designed to isolate the effect of photoperiod on colostrum, by housing Holstein and Jersey cows in a temperature-controlled barn during the last two months of pregnancy and exposing them to varying daylengths. Cows were exposed to either a short-day photoperiod of 8 h of light per day or a long-day photoperiod of 16 h of light per day. When the cows gave birth, they were milked and the amount of colostrum produced and the components of the colostrum were evaluated. A Brix refractometer, which is widely used by farmers to estimate colostrum quality as it is an on-farm tool that estimates colostrum antibody content, was also used in this study. Cows were returned to ambient photoperiod and milk, fat and protein production were tracked for 15 weeks. I found that altered photoperiod had no effect on colostrum yield, antibody content or other components of colostrum. However, Jersey cows had a higher Brix score, fat, protein, antibody IgA and antibody IgM. After calving, milk production was not affected by photoperiod treatment, likely because of irregular lighting exposure after calving. These data indicate that photoperiod alone may not be causing the seasonal variations associated with colostrum production.

Therefore, a second study was conducted to evaluate the effects of photoperiod and THI together on subsequent colostrum production in Holstein and Jersey cattle by month. Colostrum production and weather data were collected for cows housed in ambient photoperiod and THI for the last two months of pregnancy from two different farms. Cows were divided into a bottom (1), middle (2) and top (3) third based on their photoperiod exposure. Holstein cows produced more colostrum than Jersey cows in each photoperiod category. For both breeds, photoperiod category 1 cows produced less colostrum than cows in photoperiod category 2 and 3. Brix score did not differ by breed but differed by farm and photoperiod category with farm 1, photoperiod category 3 cows having increased Brix score compared to farm 2, photoperiod category 1 and 2 cows. Colostrum components for Jersey cows did not differ by photoperiod category. However, colostrum volume, Brix score, protein and SNF were all impacted by THI and (or) photoperiod variables in predictive modeling. This indicates that colostrum yield and quality in Holstein and Jersey cows are similarly impacted by both photoperiod exposure and THI exposure during the last two months of pregnancy.

Data from these studies are the first to show the isolated effect of photoperiod on colostrum production in Jersey cows and the second showing data on Holstein cows. Recommendations have already been made to dairy producers to limit photoperiod exposure during the last two months of pregnancy in order to increase milk production post-calving. This study shows that limiting photoperiod will not compromise colostrum production in cows. However, I also found that colostrum production is also impacted by THI exposure and that colostrum yield and quality have inverse relationships with photoperiod and THI exposure. Whereas colostrum yield increases with increased photoperiod and THI, Brix score decreases. Therefore, managing for increased colostrum quality is compromised by colostrum yield. This study also found that the widely accepted indirect measure of antibody content, the Brix score, was not a reliable estimate of antibody content and instead, a better indicator of solids content of colostrum.

In conclusion, these data show that photoperiod alone does not impact colostrum production, rather a combined effect of photoperiod and THI are responsible for seasonal variation in colostrum and differences between breeds of cow are also evident. In addition, Brix score may not be the best indicator of colostrum quality and could be replaced by more reliable methods by dairy farmers to ensure that adequate colostrum is fed to calves. Future studies will need to explore differences in response to photoperiod vs. THI alteration and explore genetic associations with colostrum production, to identify which genes are associated with increased colostrum quality in Jersey cows so that we may genetically select for increased colostrum quality.

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LIST OF ABBREVIATIONS

AA-NAT - Arylalkylamin N-Acetyltransferase

APC - Antigen Presenting Cell

B Cells - B Lymphocytes

BHBA - β-hydroxybutyrate

BSA - Bovine Serum Albumin

BVDV - Bovine Viral Diarrhea Virus

CU - Close-Up

DHIA - Dairy Herd Information Association

EGF - Epidermal Growth Factor

ELISA - Enzyme Linked Immunosorbent Assay

FO - Far-Off

FPT - Failure of Passive Transfer

Ig - Immunoglobulin

IGF-1 - Insulin-like Growth Factor I

IGF-2 - Insulin-like Growth Factor 2

IL - Interleukins

INF - Interferons

LDPP - Long-Day Photoperiod

LGN - Lateral Geniculate Nucleus

MAC - Membrane Attack Complex

MAT - Maximum Ambient Temperature

MBL - Mannose Binding Lectin

MHC - Major Histocompatibility Complex

mTHI - Maximum Temperature-Humidity Index

NAS - N-Acetyl-serotonin

NK - Natural Killer

PHOTO - Average Photoperiod Exposure

pRGC - Photosensitive Retinal Ganglion Cell

PRR - Pattern Recognition Receptors

PVN - Paraventricular Nucleus

RH - Relative Humidity

RID - Radial Immunodiffusion

SCN - Suprachiasmatic Nucleus

SCS - Somatic Cell Score

SDPP - Short-Day Photoperiod

T Cells - T Lymphocytes

TFG-β1 - Transforming Growth Factor β1

TGF-β2 - Transforming Growth Factor β2

TGs - Triglycerides

THI - Temperature Humidity-Index

TLR - Toll-Like Receptor

TNF - Tumor Necrosis Factor

INTRODUCTION

Colostrum is the term used to describe the “first milk” that an animal produces after giving birth to offspring. While first recorded in 1570 in Latin, it is derived from similar words in other languages that date back to 7500 to 6000 BC (Lewis and Short, 1879; Chang et al., 2015). Evolutionary development of modern-day mammalian characteristics (birth to live offspring, hair, milk production) occurred in varying order, meaning at any one time, some species exhibited one of the above-mentioned characteristics, while another species displayed another (Oftedal, 2012). However, it is generally believed that mammary glands were the first of the mammalian traits to evolve and arose from glands on the skin associated with hair follicles. These glands may originally have been used to deliver calcium and other nutrients to eggs during incubation (Oftedal, 2012). This “milk” allowed animals to increase the chances of their offspring surviving to hatching (Oftedal, 2012). Subsequent development of viviparity – retention of the embryo in the reproductive tract and development inside the mother - further increased chances of offspring survival due to birth of an offspring that is stronger and more viable (Roberts et al., 2016). Placental development occurred with the transition to viviparity from oviparity (egg-laying) and placentas have continued to evolve into different types (Roberts et al., 2016).

In many species, neonates begin to establish an effective immune system while still *in-utero* (Tizard, 2017). Maternal antibodies produced by the mother and in circulating blood are shared with the fetus’ blood supply via the placenta (Porter, 1976). Unlike these species, the synepitheliochoral placental type of cattle separates the fetal and maternal blood supply to a greater degree and prevents the transfer of immunoglobulins

(**Ig**) or antibodies to the calf while *in-utero* (Barrington and Parish, 2001). Therefore, calves are born Ig deficient and must ingest and absorb antibodies from colostrum to fill the gap in immunity until the calf's immune system matures (Weaver et al., 2000).

On farm tools such as the Brix refractometer and colostrometer are utilized by producers to estimate Ig content of colostrum. However, reliability of these tools varies widely (correlation of 0.43 to 0.77 with IgG content) and estimates are sensitive to environmental factors during testing (Bielmann et al., 2010). When colostrum quality is estimated to be poor (< 50 g/L of IgG), producers must turn to alternative sources of colostrum than the dam (Geiger, 2020). Colostrum can be frozen and stored for up to a year without impacting Ig content (Erikson and Kalscheur, 2020), or fresh colostrum from another dam calving during the same time can be utilized. However, when these are not an option, producers must turn to colostrum replacers or supplements which cost on average, $40 per dose, per calf. Therefore, avoiding the need to purchase colostrum replacer by having adequate colostrum production by cows is in the producer's best interest.

Despite these methods for estimating colostrum quality and alternative sources of colostrum when dam colostrum is inadequate, an estimated 19% of calves in the United States do not consume adequate volume of immunoglobulins from colostrum and experience failure of passive transfer (**FPT**) (Beam et al., 2009). Roughly 16% of calves that experience FPT will die, while those that survive will have long-term effects on health and productivity. Calves that received 2 liters of colostrum at birth produced 2,607 kg less milk during their first 2 lactations compared with calves that received 4 liters of colostrum at birth (Raboisson et al., 1998; Faber et al., 2005).

While the importance of colostrum to calf health has been known for decades, there is limited understanding of how individual colostrum components contribute to the development and function of the pre-weaned calf’s immune system and overall calf health. In addition, despite intensive management for ideal colostrum production that contains a minimum of 50 grams per liter of IgG, colostrum quality and quantity differ vastly among cows, making adequate colostrum consumption for calves more difficult to achieve (Cortese, 2009). The purpose of this literature review is to better understand the body of work available on colostrogenesis, factors that affect colostrum production, interaction of colostrum composition with calf health, proposed methods to improve colostrum production, and proposed interventions for improving calf health.

CHAPTER 1: LITERATURE REVIEW

COLOSTROGENESIS

Colostrum production in the mammary gland begins around 5 weeks before parturition in pregnant cattle and is coordinated chiefly by the endocrine system (Brandon et al., 1971). Serum estrogen concentrations increase around 4 weeks before parturition, serum corticosteroids, growth hormone and prolactin increase 1 week prior and progesterone begins to decline 2 weeks prior, before sharply declining 1-2 days before parturition (Akers, 2016). This hormone profile drives structural and functional differentiation of the mammary secretory cells in preparation for the onset of colostrum and milk production (Akers, 2016). The RNA to DNA ratio, number of ribosomes, endoplasmic reticulum and mitochondria increase in each alveolar cell to synthesize colostrum and milk components (Products, 1988). Compared with milk, colostrum contains increased levels of proteins, fats, hormones, growth factors, prostaglandins, enzymes, cytokines, minerals and vitamins (Georgiev, 2008). Several components make up colostrum and play a role in calf health. The major components in descending order of abundance are water, protein, fat, carbohydrates, growth factors and cells (McGrath et al., 2016). Synthesis of these components and the mechanism by which they enter the mammary gland and are found in colostrum is described.

Protein. After water, protein makes up the largest proportion of colostrum (12.7%) and is further classified into casein (α-casein, β-casein, γ-casein, κ-casein) and whey (α-lactalbumin, β-lactoglobulin, bovine serum albumin, immunoglobulins, lactoferrin, transferrin). (McGrath et al., 2016; Morrill et al., 2012). Within whey, immunoglobulin classes A, G and M comprise the most important immunomodulatory factors for calves and account for 70-80% of total colostral protein, ranging from 20.37 – 228.59 g/L (Korhonen et al., 2000; Larson, 1992). These antibodies are comprised of four protein chains linked by disulfide bonds and are produced by maternal plasma cells (Amzel and Poljak, 1979; Roux et al., 1977). Subclass IgG_1 comprises the largest portion of immunoglobulins (35 – 75 g/L) and is selectively transported into the mammary gland by binding to Fc receptors located on alveolar epithelial cells after being produced by maternal plasma cells in the spleen and lymph nodes (Butler, 1983; Ahmann et al., 2021). IgG_1 receptors are up-regulated during late gestation before being down-regulated during lactogenesis (Barrington et al., 2001). This coincides with changes in serum estrogen, progesterone and prolactin; leading to a transfer of IgG_1 from circulating blood into the mammary gland (Barrington et al., 2001). IgG_2 is also present in colostrum, but at levels 5 to 10 times less (1.9 to 6 g/L) than that of IgG_1 (Larson, 1992). Unlike IgG, IgA and IgM are thought to be produced locally within the mammary gland (Roux et al., 1977). IgA and IgM producing plasma cells migrate from gut associated lymphoid tissue to the mammary gland (Brandtzaeg, 2010). Within the mammary gland, IgA and IgM are transported across mammary epithelial cells into mammary secretions via the polymeric immunoglobulin receptor after production (Mostov and Kaetzel, 1999). IgA and IgM are present in less quantities than IgG_1 and average 1.7 – 4.4 and 4.2 – 4.9 g/L respectively (Ahmann et al., 2021). By day 3 post-calving, immunoglobulin content has decreased by 94% and accounts for only 1% of milk protein (Madsen et al., 2004).

The other whey proteins and the casein proteins are synthesized from amino acids derived from either the blood stream or from amino acids synthesized by secretory cells (Akers, 2016). Therefore, dietary protein intake impacts casein production significantly

(Sutton, 1989). After ingesting feedstuffs, protein is either degraded in the rumen by microbes or passes through the rumen and is broken down in the abomasum by trypsin (Cammack et al., 2018). Amino acids are absorbed into the blood stream via the small intestine and transported into the mammary gland via numerous amino acid transporter systems, which are specific for each amino acid (Wu et al., 2020). Once amino acids are present inside mammary epithelial cells, transfer-RNA transfers the amino acids to the ribosome, which then reads messenger-RNA which provides instruction to the ribosome for protein synthesis (Akers, 2016).

The whey proteins α-lactalbumin, β-lactoglobulin and bovine serum albumin (**BSA**) average 3, 7.9-30, and 1.21 g/L in colostrum but decline to 1.2, 3.3 and 0.13 g/L respectively in mature milk (Levieux et al., 2002; Park, 2009; Levieux and Ollier, 1999). α-lactalbumin and β-lactoglobulin serve as sources of protein for calf growth and development, while BSA serves as a transporter of molecules into the mammary gland and is therefore an indicator of the blood-milk barrier permeability (Echeverry-Munery et al., 2021; Terosky et al., 1997). Lactoferrin and transferrin are highest in colostrum at 0.83 and 1.07 g/L, respectively, before dropping to 0.09 and 0.02 g/L within 24 h (Sanchez et al., 1988). Both play a role in binding iron, which is a nutrient required for bacterial growth (Sanchez et al., 1992). While their biological role is unknown, it is thought that based on their iron binding activity, that lactoferrin and transferrin have antiviral properties within the mammary gland and impact development of the newborn calves' intestinal flora (Ribadeau-Dumas, 1983).

Like the whey proteins, the milk protein, casein, is greater concentration in colostrum and decreases with subsequent milkings by 60% (Madsen et al., 2004).

Colostrum averages 26 g/L of casein (Park, 2009), which is like levels found in milk (25 g/L) (Cerbulis and Farrell, 1975), however, concentration is drastically reduced due to increased colostrum volume, representing a 60% decline in concentration. Of the subtypes, α-casein accounts for ~40% of the total casein fraction, followed by β and γ-casein at ~30% and then κ-casein at ~30% or less (Sobczuk-szul et al., 2013). With subsequent milkings, the percentage of casein that is α-casein increases, κ-casein decreases until stabilizing 3 days post-calving, while β and γ-casein remains constant (Sobczuk-szul et al., 2013).

Additional proteins present in high quantities in colostrum are cytokines (Hagiwara et al., 2000). Cytokines are a broad class of small proteins secreted by a variety of cells that interact with other cells to modulate function of the immune system (Krueger et al., 2011). The primary cytokines present in colostrum are interleukins (IL), tumor necrosis factors (TNF) and interferons (INF) (McGrath et al., 2016). Specifically, IL-1β, IL-6, IL-1, TNF-α and INF-γ are greater in colostrum than mature milk (Hagiwara et al., 2000). Mammary epithelial cells, leukocytes and macrophages produce cytokines in response to various stimuli (Brenmoehl et al., 2018). It is thought that these cytokines may play a role in developing neonatal immunity (Chase et al., 2008).

Fats. Fat comprises the second largest solids portion of colostrum (7%) after protein and is greater than fat content of milk (Hammon et al., 2020; Foley and Otterby, 1978). Milk fat is primarily triglycerides (TGs): a glycerol bound to three fatty acid molecules. Triglycerides are synthesized from two sources: diet and de novo synthesis within the mammary gland. Within the rumen, bacteria hydrolyze lipids from feedstuffs, resulting in separation of glycerol and the fatty acids and presence of both saturated and unsaturated fatty acids (Jarvis and Moore, 2010). A portion of the unsaturated fatty acids are then biohydrogenated to generate saturated fatty acids, which are transported to the small intestine for absorption (Jenkins, 1993). Lipoproteins present in plasma are responsible for transporting fatty acids from the intestine to the mammary gland (Bauchart, 1992). For *de novo* fatty acid synthesis, acetate and BHBA (β-hydroxybutyrate) serve as precursors (Akers, 2016). After entering mammary epithelial cells via passive diffusion, acetate and BHBA are converted to acetyl-CoA by binding to pyruvate. Acetyl-CoA is then carboxylated to form malonyl-CoA and medium or long-chain fatty acids are synthesized by the rough endoplasmic reticulum via membrane-bound fatty acyl transferases (Mu et al., 2021). Once assembled, TGs aggregate and are packaged into lipid droplets which are secreted into the lumen (Bauman et al., 2006).

Carbohydrates. Lactose is the primary carbohydrate in colostrum and milk, but unlike the previous components, is found in less quantities in colostrum (1.5 to 2.3%) than milk (4.7%) (Zarcula et al., 2010; Fox et al., 2015). The major role of lactose is to regulate water and osmotic content (Jenness, 1985). Lactose production causes water to move from the cytoplasm of mammary epithelial cells into the mammary secretory vesicles and eventually, the lumen (Kuhn et al., 1980). Therefore, as milk production increases post-calving, there is also an increase in lactose concentration (Fox et al., 2015). Lactose is a disaccharide sugar comprised of a glucose and galactose subunit, synthesized via lactose synthase, comprised of galacosyltransferase and α-lactalbumin (Watkins and Hassid, 1962). Complex carbohydrates and simple sugars from the diet are degraded by rumen microbes, which produce volatile fatty acids (VFAs), specifically propionic acid (Sutton, 1971). Propionic acid is absorbed across the rumen wall and enters circulation where it travels to the liver to undergo gluconeogenesis (Ariello et al., 1989; Zhang et al., 2017). Glucose generated in the liver then travels via the blood stream to the mammary gland and enters mammary epithelial cells by utilizing glucose transporters (GLUTs). Once inside mammary epithelial cells, glucose is phosphorylated and then converted to UDP-galactose in the cytoplasm. Golgi vesicles then take up glucose and UDP-galactose to synthesize lactose (Zhao, 2014). Other carbohydrates are also present in colostrum, including fructose, glucosamine and galactosamine among others, however they are present in low quantities.

Growth Factors. Colostrum is rich in growth factors which decline sharply in number shortly after calving (McGrath et al., 2016). Insulin-like growth factor 1 (**IGF-1**) and 2 (**IGF-2**) are the most abundant, ranging from 50-2000 ug/L and 200-600 ug/L respectively, before dropping to less than 10 ug/L in mature milk (Pakkanen and Aalto, 1997). Both are synthesized locally in the mammary gland, however the majority is transported from circulating blood into the mammary gland after production in the liver (Campbell et al., 1991; Prosser, 1996). IGF-1 and IGF-2 stimulate mammary growth, blood flow and milk secretion as well as aid in neonatal gut development in calves, which will be detailed later (Prosser, 1996). Epidermal growth factor (**EGF**) is also present in colostrum, produced locally and ranges from 4 - 324 ug/L. EGF functions as an important stimulator of mammary growth and development (Yagi et al., 1986; Iacopetta et al., 1992; Plaut, 1993). Transforming growth factor β-1 (TFG-β1) and 2 (TGF-β2) both play a critical role in mammary gland remodeling and cellular proliferation necessary for lactation onset after the dry period (Mitz and Veloria-Petit, 2019). At lactation onset, TFG-β1 and TFG-β2 average 12.4 – 42.6 ng/mL and 150 – 1150 ng/mL, respectively, before dropping sharply by 2-3 days of lactation to 0.8 – 3.49 ng/mL and 12.6 – 71.3 ng/mL (Ginjala and Pakkanen, 1998; Pakkanen, 1998). Betacellulin, another growth hormone, averages 2.61 ng/mL and drops more than 75% by day 3 post-calving. While it is thought to aid in neonatal and mammary growth and development, betacellulin's role is not well understood (Bastian et al., 2001).

Cells. Colostrum contains 1,000,000 – 3,000,000 cells/mL, whereas mature milk from non-infected cows is less than 200,000 cells/mL (Lee et al., 1980; Bradley and Green, 2005). The cells in colostrum are almost exclusively leukocytes (Lee et al., 1980). After these cells are produced in bone marrow, they enter blood circulation and exist in storage pools until stimulated by chemoattractants (Paape et al., 1977). Macrophages, leukocytes and epithelial cells existing locally in the mammary gland release chemoattractants in response to infection stimuli in order to initiate an inflammatory response and recruit more leukocytes to the site of infection (Paape et al., 2002). Calves receiving colostrum containing maternal leukocytes develop immune cells that are able to identify antigens, and therefore mount an appropriate immune response, more quickly than calves that do not receive maternal leukocytes in their colostrum (Reber et al., 2005)

FACTORS AFFECTING COLOSTRUM PRODUCTION

While the physiology of colostrogenesis and synthesis of colostrum components in dairy cattle has been studied extensively, numerous factors influence these biological processes. Genetic factors such as breed or genetic potential as well as environmental factors including vaccination status, nutrition and metabolic status all influence both the quality and quantity of colostrum produced (Puppel et al., 2019). As previously mentioned, calves are born Ig deficient and must ingest colostrum that is rich in immunoglobulins (Weaver et al., 2000). Research shows that calves should ingest at least 150 – 200 g of IgG shortly after birth in a 3 to 4 L volume (Cortese, 2009; Godden et al., 2019). Therefore, 50 g/L is the industry standard threshold for high quality colostrum (Geiger, 2020). Calf serum IgG levels should reach 10 g/L to ensure adequate immunity (Ganchev et al., 2015). However, colostrum volume and quality vary substantially from cow to cow (2.8 to 26.5 L and 13 to 256 g/L, respectively), resulting in 19% of calves not ingesting adequate levels of IgG (termed failure of passive transfer – FPT) and accounting for 30% of pre-weaned calf deaths (Morin et al., 2001; Conneely et al., 2013; Wells et al., 1996). Genetic and environmental factors influencing colostrum production are described below.

Breed. Breed is a significant factor that accounts for differences in both colostrum volume and colostral components (Puppel et al., 2019). As Holstein and Jersey cows account for 81.4% and 12.2% of the US dairy cow population respectively, the breed discussion will focus on these two breeds (Guinan, 2019).

Muller and Ellinger (1981) showed that Jersey cows had the highest percentage of total Ig in their colostrum (9.04%) while Holstein cows had the lowest (5.6%). Average IgG content of Holstein colostrum ranged from 57.65 to 73.4 g/L compared to Jersey colostrum which ranged from 72.81 to 83.8 g/L (Hassan et al., 2020; Elsohaby et al., 2017; Esohaby et al., 2018; Chigerwe et al., 2008; Quigley et al., 2013; Morrill et al., 2015; Silva-del-Rio et al., 2017). While authors suggested that Holstein cow colostrum has decreased Ig content compared to Jersey cow colostrum, Coleman et al. (2015) and Morrill et al. (2012) found no difference in Ig content between breeds. Recent data shows average Holstein cow colostral IgG to be 91.31 g/L, much greater than previous findings and greater than Jersey cow colostrum averages (Costa et al., 2021). The discrepancy may be due in part to the method chosen to analyze Ig content. A positive moderate phenotypic correlation (0.36) was observed for IgG between enzyme linked immunosorbent assay (ELISA) versus radial immunodiffusion (RID) assay, with RID values greater than ELISA (Gelsinger et al., 2015; Dunn et al., 2018). Because limited studies have evaluated Ig levels in colostrum between Holstein and Jersey cows it is difficult to distinguish breed differences in Ig production from environmental factors. However, colostrum volume between breeds appears to have a greater relationship with the environment.

Brix score indirectly measures immunoglobulin content by measuring the total solids content of colostrum (Moore et al., 2009). An inverse relationship between Ig concentration or Brix and colostral volume is reported (Cabral et al., 2016; Silva-del-Rio et al., 2017; Zentrich et al., 2019; Borchardt et al., 2022; Westhoff et al., 2022), however, some studies found no relationship between colostral volume and Ig concentration (Baumrucker et a., 2010; Zarei et al., 2017). As Jersey cows generally produce decreased amounts of milk and colostrum compared to Holstein cows, Jersey cows generally have increased quality colostrum. Jersey cows average 4.0 to 4.3 kg of colostrum at the first milking post calving (Silva-del-Rio et al., 2017; Gavin et al., 2018; Valldecabres and Silva-del-Rio, 2021) while Holsteins average 6.1 to 7.0 kg (Zarei et al., 2017; Kehoe et al., 2011; Soufleri et al., 2021).

Other components of colostrum may differ among breeds as well. A direct comparison study found total protein, solids nonfat and overall density of Jersey colostrum to be significantly increased compared with colostrum from Holsteins

(Sobczuk-Szul et al., 2013). When colostrum from Holsteins, Ayrshires, Jerseys and Guernseys was compared, Holsteins were found to have the lowest specific gravity, solids nonfat, total protein and ash content and the greatest lactose percentage, while Jersey cow colostrum had the greatest ash and solids content and the lowest fat percentage (Parrish et al., 1950). However, a nationwide evaluation based on pooled colostrum samples found no differences in fat, protein, lactose, other solids or total solids between colostrum from Holstein and Jersey cows (Morrill et al., 2012). Holstein cow colostrum averages 4.6 - 6.4% fat, 17.8 – 18.5% protein, 2.0 - 2.2% lactose and 25.8 – 27.2% total solids while Jersey cow colostrum averages 5.8% fat, 22.6% protein, 1.2% lactose and 23.6 – 31.3% total solids (Zarei et al., 2017; Soufleri et al., 2021; Quigley et al., 1994; Silva et al., 2021). These averages indicate little difference in fat and total solids content, but potential differences in protein and lactose, with Jerseys having greater protein and less lactose.

Genetics. In addition to differences in colostrum production by breed, an animals' genetic potential also plays a role in accounting for colostrum production differences. Low to moderate heritability estimates for total solids (0.27), fat (0.21), protein (0.19), lactose (0.15) and colostrum volume (0.04) were reported in Holstein cows (Soufleri et al., 2019). Colostral IgG, IgG_1, IgA and IgM concentrations have been linked to 14 candidate functional genes in Holstein cows. These genes are responsible for immune processes, including adaptive and innate immunity, control of inflammation, neutrophil development and direct formation of Igs (Lin et al., 2022). In addition, 1 locus has been identified to be strongly associated and 6 moderately associated with colostrum volume, located on chromosomes 2, 10, 13, 17 and 18 (Kiser et al., 2018). One locus on chromosome 3 was moderately associated with colostrum quality (Kiser et al., 2018). Of the 8 loci identified, 5 contained candidate genes with functional relevance to colostrum production (Kiser et al., 2018). Heritability estimates for colostrum volume reported in Jersey cows is strong (0.76), whereas colostrum quality (via indirect measurement with Brix refractometer) are weak (0.19) (Kiser et al., 2018).

Parity. Number of pregnancies or parity is associated with age, which are both factors that influence colostrum production (Gavin et al., 2018; Zarei et al., 2017; Soufleri et al., 2021). Primiparous Jersey cows (first pregnancy and lactation) average greater colostrum production than multiparous cows (second or greater pregnancy and lactation) (4.92 kg vs. 3.67 to 4.09 kg) and total solids were greater for primiparous than second or 3+ lactation animals (26.6% vs. 25.0% to 25.8%) (Gavin et al., 2018). Data in Holstein cows does not reflect this trend, with first parity Holsteins producing less colostrum (5.9 L) than all other parities (7.0 to 7.4 L). (Zarei et al., 2017; Soufleri et al., 2021). Differences in IgA, IgG, IgM and total Ig were not detected among parities in Holstein cows; however, other measures of colostrum quality differ by parity (Zarei et al., 2017; Costa et al., 2021). Fat and total solids were greatest for first parity Holsteins (6.7% and 29.2% respectively) compared to other parities (3.87% to 4.1% fat; 25.5% to 27.2% total solids) (Zareai et al., 2017; Soufleri et al., 2021). However, another study found conflicting data, with total solids being greater in four plus parity animals compared to one, two and three parity cows (26.8% vs. 24.4% to 25.8%; Soufleri et al., 2021). Protein was greatest for three plus lactation animals (Zarei et al., 2017) and four plus lactation cows in a second study (Soufleri et al., 2021), however, lactose was greatest for second lactation animals (Zarei et al., 2017; Soufleri et al., 2021). When colostrum from both breeds were pooled, IgG increased with parity, and fat, protein, lactose and other solids were lowest for second lactation animals and highest for three plus lactation animals (Morrill et al., 2012).

Overall, first lactation Jersey cows produce greater volume and have greater total solids. Holstein cows produce less volume colostrum and have inconsistent results for total solids. Protein in Holstein cow colostrum consistently increases with parity, while lactose is greatest for second lactation animals before dropping again in later lactations.

Dry Period Management. The dry period is the 45 to 65 days immediately before calving during which the cow is not milked. This period is critical for subsequent colostrum and milk production because structural and functional differentiation of the mammary secretory cells occurs. Adequate dry period length, nutrition, vaccination and management is essential for colostrum production.

The length of the dry period is critical to allow proper involution and rejuvenation of the mammary gland to prepare for lactation onset after the next calving event (Annen et al., 2007). The recommended minimum dry period length of 45 to 60 days allows for adequate mammary gland remodeling and subsequent colostrum and milk production (Shoshani et al., 2014). Holsteins with a zero- or 30-day dry period produce less colostrum at calving (5.1 to 5.3 kg) compared to cows with a 60-day dry period (7.7 kg). However, no differences in IgG or IgM concentration were detected (Mayasari et al., 2015). In addition, Jersey cows with a 45-day dry period have a 1.69 × greater odds ratio of producing lower colostrum volume compared to Jerseys with a 65-day dry period (Gavin et al., 2018).

Nutrition during the dry period not only impacts colostrum production but can have direct effects on the calf while *in-utero* and therefore, is closely managed. Providing a decreased energy diet (0.61 UFL/kg of dry matter) did not affect colostrum composition or total Ig content but did increase IgA content in Holstein cattle (Nowak et al., 2012). Similarly, increased IgG content was found in colostrum of cows fed a normal or slightly elevated energy diet (125% of energy requirements) compared to cows fed a high energy diet (150% of energy requirements) (Mann et al., 2016). No effect on any other parameters of colostrum production were found.

Vaccination during the dry period is critical for neonatal calf health, by increasing the concentration of specific immunoglobulins in colostrum (Crouch et al., 2001). When cows are vaccinated at 30 – 60 days before expected calving with vaccines for rotavirus, coronavirus, and *Escherichia coli* (K99), there is a significant increase in specific antibodies to all three in the colostrum (Crouch et al., 2001; Pinheiro et al., 2022). Vaccination at dry off and again four weeks later with a *salmonella* bacterial extract also increased specific antibodies in colostrum and subsequently increased calf serum specific antibodies after the colostrum was ingested by calves (Smith et al., 2014). These studies show the specific impact of vaccines on antibody number in colostrum without any effects on other colostral components.

Heat stress during the dry period alters mammary function and compromises mammary regrowth during the late dry period (Tao et al., 2011; Tao et al., 2018). In heifers, this results in reduced colostrum Ig production and protein content of colostrum, but no differences in colostrum volume, fat, lactose, or casein content (Nardone et al., 1997). However, no differences in colostral Ig content were observed in heat stressed cows (Tao et al., 2012). Colostrum volume was also not different; however, colostrum density was reduced in cows experiencing heat stress (Karimi et al., 2015). Colostrum density is an approximate measurement of total colostrum protein, indicating that some portion of colostral proteins were reduced in these animals.

Season of calving may alter colostrum production based on temperature, humidity, and photoperiod exposure during the dry period. Multiparous Jersey cows that calved in June produced 6.6 kg of colostrum compared to cows that produced 1.3 kg in December. Primiparous Jerseys also experienced a drop from 6.5 kg in June to 4.2 kg in December. The temperature humidity index (THI) and photoperiod at the time of calving and one month prior to calving were highly correlated with colostrum volume for both primiparous and multiparous Jersey cows. As THI and photoperiod increased, so did colostrum production (Gavin et al., 2018). Holstein cows responded similarly, with primiparous cows having the highest colostrum production in April (4.1 kg) and the lowest in November (3.2 kg) and multiparous cows having the greatest colostrum production in May (5.5 kg) and the lowest in October (3.8 kg) (Borchardt et al., 2022). Similarly, data in Holstein cows showed that colostrum yield was positively correlated with the number of days above 23 °C during the 21 days before calving (Cabral et al., 2016) and with average THI > 69.2 during the 7 days before calving (Westhoff et al., 2023). Greater average light intensity during the 14 days before calving was also associated with increased colostrum yield (Westhoff et al., 2023).

Brix score follows an inverse relationship with season, being the highest in winter for primiparous (December – 26.8%) and multiparous (February – 27.5%) cows and the lowest during the summer (August – 23.9% primiparous, 25.7% multiparous) (Borchardt et al., 2022). Brix score was negatively associated with THI during the 7 days before calving, with the greatest Brix scores in cows with < 50.1 average daily THI (Westhoff et al., 2023). Brix was also negatively associated with THI during the 14 and 21 days before calving, with lowest Brix scores in cows exposed to >72 THI (Zentrich et al., 2019). In addition, IgG was negatively correlated with the number of days above 23 °C (Cabral et al., 2016). Colostrum from cows calving during a high air temperature season (average THI 74.3 ± 0.5) had significantly less IgG content (59.5 ± 1.6 g/L) compared to cows calving during a low air temperature season (average THI 43.6 ± 0.8; 69.0 ± 2.6 g/L) (Trifkovic et al., 2018). Cows experiencing heat stress during the dry period may result in increased colostrum volume via dilation of blood vessels, which increases blood vessel permeability and may lead to an increase in colostrum production (Cabral et al., 2016).

Thus far, increased colostrum volume is associated with increased temperature and summer months while Brix score has an inverse relationship with temperature and season. However, one study found an opposite effect, with increased colostral IgG for cows exposed to THI > 70 (72.6 g/L) and lowest for cows exposed to THI < 40 (64.2 g/L) (Shivley et al., 2018) and others found no differences by season for IgG (Pritchett et al., 1991; Baumrucker et al., 2010) or colostrum volume (Zarei et al., 2017).

These data suggest light exposure impacts colostrum production. The next section will review current knowledge regarding the effects of light exposure in cattle including the mechanism of action and physiological effects.

PHOTOPERIODIC EFFECTS ON CATTLE

Photoperiod refers to the duration of light exposure that an animal receives during a 24 h period (Aschoff, 1955). First known reports by Peters and collaborators in 1978 suggested that photoperiod can directly affect milk production in lactating dairy cows (Peters et al., 1978). Subsequent studies have shown that photoperiod impacts growth, mammary gland development, immune system function, as well as other bodily functions by altering hormone and receptor levels and sensitivity. Due to the ease with which photoperiod can be manipulated, the dairy industry utilizes photoperiod as a non-invasive method to improve milk production. However, despite numerous studies indicating the effectiveness of photoperiod manipulation to improve milk production, neither the physiological mechanism nor the effect on other bodily processes have been entirely elucidated (Dahl et al., 2000).

Photoperiod Mechanism. Light is detected within the retina of the eye by rod and cone cells, the primary photoreceptors (Ebrey and Koutalos, 2001). Rods specialize in detecting very dim light whereas cones function in daylight (Kawamura and Thacibanaki, 2014). Within rods and cones are opsins, which convert the light signal to a nerve impulse via a series of enzymatic reactions, resulting in membrane hyperpolarization of the rod or cone cell (Plachetzki et al., 2010). These nerve impulses are then transmitted to retinal ganglion cells which transfer the impulse along the optic nerve to the lateral geniculate nucleus (**LGN**), located in the thalamus. Finally, neurons within the LGN travel to the primary visual cortex where the information is processed and the light/dark and image is interpreted by the brain (Stacy et al., 2020).

A third type of photoreceptor, known as photosensitive retinal ganglion cells (**pRGCs**) was identified in the 1980’s as the primary photoreceptor responsible for maintaining circadian rhythm (Gooley et al., 2012; Czeisler et al., 1995). Circadian rhythm refers to endocrine and behavioral changes that occur cyclically in a 24 h period for cows. Within pRGCs is a unique opsin, melanopsin, which converts the light signal to a nerve impulse in a process like the process in rods and cones, except that the result is depolarization of the cell rather than hyperpolarization (Do et al., 2009). These cells are localized and directly innervated with the suprachiasmatic nucleus (SCN) (Hannibal et al., 2002). In response to the nerve impulse stimulated by light, the SCN secretes gamma-amino butyric acid, which inhibits neuron synapses in the paraventricular nucleus (PVN) of the hypothalamus, thereby interrupting the signal transmission to the pineal gland. When there is no light, the SCN secretes glutamate, which transmits the signal from the PVN to the pineal gland (Arendt and Aulinas, 2022). This signal triggers the release of norepinephrine, which stimulates transcription of arylalkylamin N-acetyltransferase (**AA-NAT**), the precursor for melatonin production by pinealocytes (Amaral and Cipolla-Neto, 2018).

Within pinealocytes, melatonin production begins with tryptophan conversion to serotonin, then serotonin conversion to N-acetylserotonin (**NAS**) via AA-NAT, and finally conversion of NAS to melatonin via acetylserotonin O-methyltransferase (Arendt et al., 2022). Availability of norepinephrine, serotonin and AA-NAT regulate the release of melatonin (Arendt et al., 2022). After synthesis, the pinealocytes passively secrete melatonin into blood circulation in a pulsatile manner (Reiter et al., 1991). In the body, melatonin has a short half-life of 10 to 40 minutes and 90% of circulating melatonin is cleared after a single passage through the liver (Pardridge and Mietus, 1980; Kopin et al., 1961; Kveder and McIsaac 1961).

In the absence of light, melatonin production is high and constant, but during periods of light, melatonin production is low (Buchanan et al., 1992; Hedlund et al., 1977). In cattle, light detection and melatonin production are sensitive - light can be detected at intensities as low as 5 lux (the unit of illuminance equivalent to one lumen per square meter) and melatonin production can be suppressed by light exposure as brief as one minute during darkness (Phillips and Weiguo, 1991; Illnerova and Vanecek, 1979). In addition, constant light or constant darkness do not result in complete disruption of a cow's circadian rhythm. Rather, when animals are exposed to continual darkness, AA-NAT and melatonin levels develop a cyclic pattern that is slightly longer than 24 h and is based on animal activity level (Reiter, 1991). Likewise, when cows are exposed to continual light, they lose normal circadian rhythm and exhibit physiological responses that are consistent with short-daylength light exposure (Dahl et al., 2000).

A cow's perception of "dawn" is determined by the cows' circadian rhythm and the beginning of light exposure. In addition, animals that have acclimated to a photoperiod schedule will anticipate dawn, evidenced by a decrease in melatonin levels to daytime concentrations before light onset (Reiter, 1991). After dawn, the animals' circadian clock then tracks photoperiod relative to dawn to determine daylength (Dahl et al., 2000). In cows, when light is detected 13 to 15 h after the perceived dawn, it is considered a long day, whereas if darkness is detected, it is a short day (Dahl et al., 2000; Evans and Hacker, 1989). This period is considered the "photosensitive" period, as exposure to darkness after dawn, but prior to the photosensitive period will not cause physiological responses consistent with short-daylength if light exposure is resumed at 13 to 15 h after dawn (Evans and Hacker, 1989).

Photoperiod and Lactating Cows. Multiple studies have shown that 16 to 18 h of light per day will increase milk production by 2.5 kg per day relative to cows exposed to ambient daylength (10 to 12 h of light) or shortened daylength (8 h of light) (Dahl et al., 2000). Peters et al. (1978) demonstrated that lactating Holsteins exposed to 16 h of light per day at 39 to 93 lux had 10 to 15% increased weight gain and milk yield, compared to herd mates that were exposed to 9 to 12 h of light. Results were observed as early as 10 d post-partum, with cows exposed to long-day photoperiod producing 1.7 kg more milk daily than cows exposed to natural or ambient photoperiod. By 20 days post-partum, the difference increased to 3.1 kg more milk produced daily by cows exposed to long-day photoperiod, which was sustained until 100 days post-partum. At 100 days in milk, the treatment was switched for the groups and milk production was tracked until 140 days post-partum. Cows that previously were exposed to long-day, but now exposed to natural photoperiod for days 101 to 140 post-partum produced only 0.9 kg more milk per day than cows that were previously exposed to natural photoperiod and then exposed to long-day photoperiod. This indicated that cows exposed to increased daylength after 100 d post-partum decreases the rate of decline in milk production (Peters et al., 1978).

Numerous studies have since confirmed these findings, showing a 0.5 to 3.3 kg increase in milk production per day in cows exposed to long-day photoperiod (13 to 18 h of light daily) compared to natural photoperiod or short-day photoperiod herd mates across a variety of stages of lactation (0 to 158 days post-partum) (Peters et al., 1980; Marcek and Swanson, 1984; Stanisiewski et al., 1985; Bilodeau et al., 1989; Evans and Hacker, 1989; Phillips and Schofield, 1989; Dahl et al., 1997; Reksen et al., 1999; Miller et al., 1999; Aharoni et al., 2002; Lim et al., 2021). This increase in milk production is not always accompanied by increased dry matter intake but is seen in long-term studies where increased dry matter intake is necessary to meet increased milk production demands (Dahl et al., 2000).

The mechanism by which altered photoperiod impacts milk production is unclear. Altered melatonin production and milk production are the key physiological outcome of modified photoperiod exposure. This indicates that circulating melatonin levels likely correspond to milk production. Given that cows respond to long-day photoperiod with decreased melatonin synthesis and increased milk production, it reasons that melatonin may have an antagonistic effect on milk production. Interestingly, grazing Friesian cows administered melatonin implants during the longest days of the year produced less milk by 6 weeks and 23% less milk by 12 weeks than control cows (Auldist et al., 2006). Conversely, lactating cows in early or late lactation exposed to long-days and administered an oral melatonin bolus in the middle of the daily photoperiod for 8 weeks did not demonstrate a change in milk production compared to control cows (Dahl et al., 2000; Buchanan et al., 1993). Studies looking at the effects of melatonin supplementation on milk production are limited and remain inconclusive. However, differences in outcomes among the three studies described above are the amount and method of melatonin supplementation. Cattle administered the slow-release implant received 108 mg of melatonin (around 0.009 mg/kg per day) three different times, four weeks apart which delivered constant, low levels of melatonin. This constant melatonin exposure may remove circadian rhythm entirely from the animal rather than mimic short-daylength exposure. However, a daily oral bolus of 22.5 mg of melatonin (around 0.05 mg/kg per day) administered for 8 weeks may more closely mimic short-daylength when administered during the photosensitive-period by causing the cow to perceive short-daylength despite a longer amount of light exposure. Therefore, daily oral bolus may more closely mimic short-day photoperiod exposure over slow-release melatonin implants, however, studies have not confirmed this.

In addition to alterations in melatonin concentration in response to adjusted photoperiod, there are also changes in prolactin and IGF-1, which may have a greater influence on the milk production response. Circulating prolactin is elevated in cows exposed to long-day photoperiod (Peters et al., 1980). Prolactin is also a galactopoietic hormone, stimulating milk production and often stimulating dry matter which supports increased milk production (Lacasse et al., 2016). Therefore, it is thought that prolactin may play a role in mediating the mechanism for increased milk production in response to long-day photoperiod in lactating cows (Dahl et al., 2000). However, when cows exposed to increased daylength are also exposed to environmental temperatures below freezing, they still exhibit increased milk production, but do not show increase in prolactin levels (Peters et al., 1981). This indicates that prolactin alone does not account for the increase in milk production observed in long-day cows. Insulin-like growth factor 1 also varies in response to photoperiod and plays an important role in initiating lactation in the mammary gland as expression of IGF-I is critical for mammary gland development and differentiation during late pregnancy (Sharma et al., 1994). In response to long-day photoperiod, lactating cows exhibit increased IGF-1 (60.1 ± 2.0 vs. 52.6 ± 2.0 ng/mL) along with increased milk production compared to cows exposed to natural photoperiod length (Dahl et al., 1997). Interestingly, IGF-1 concentrations changed before a difference in milk production could be detected and was not accompanied by any changes in IGF binding protein 2 or 3 (IGFBP-2, IGFBP-3). This implicates IGF-1 as a likely mediator of the milk production response to photoperiod in cows (Dahl et al., 1997).

Photoperiod and Dry Cows. Non-lactating, pregnant, multiparous cattle are uniquely affected by altered photoperiod. Cows exposed to short-days of 8 h of light per day during the dry period and then exposed to ambient or long-day photoperiod immediately post-calving, produce more milk during their first 16 wk of lactation (Auchtung et al., 2005). Greater milk production post-calving in cows exposed to short-day photoperiods has been confirmed by numerous studies, with an average increase in milk production of 3.2 to 4.6 kg per day for short-day cows. Elevated milk production is maintained up to 17 weeks post-calving (Miller et al., 2000; Aharoni et al., 2000; Lacasse et al., 2014; Crawford et al., 2015). An increase in dry matter intake in cows exposed to short-day photoperiod was found, which may play a role in increased milk production (Miller et al., 2000; Lacasse et al., 2014). However, other studies did not find an increase in dry matter intake to explain the increased milk production, which indicates greater feed efficiency (Auchtung et al., 2005; Crawford et al., 2015). While milk yield differed with dry period photoperiod exposure, milk composition was unchanged (Miller et al., 2000; Crawford et al., 2015; Auchtung et al., 2005).

The mechanism by which short-day exposure to dry cows, but long-day exposure to lactating cows both increase milk production is conflicting. Like the hormonal effects observed with lactating cows exposed to short-days, dry cows exposed to short-days also exhibit reduced circulating prolactin concentrations, however, they have increased prolactin receptor expression in the mammary gland (Auchtung et al., 2005). An animal’s sensitivity to prolactin is greater when circulating prolactin is low, but prolactin-receptor mRNA expression is high. This sensitivity may explain how the result is increased milk production, despite decreased circulating prolactin (Auchtung et al., 2005). Prolactin and its receptor are necessary for complete differentiation of mammary epithelial cells (Akers et al., 1981a). When prolactin is inhibited prior to calving, final differentiation is inhibited, resulting in fewer fully functional mammary epithelial cells (Akers et al., 1981b). Therefore, it seems likely that the prolactin-to-prolactin receptor ratio and sensitivity are responsible for altered milk production post-calving in dry cows with altered photoperiod (Auchtung et al., 2005). In addition, while there is not an effect on IGF-I mRNA, IGF-II mRNA was increased, mammary cell apoptosis was decreased and mammary cell proliferation was increased in cows exposed to short-days during the dry period (Wall et al., 2005). Unlike IGF-I, IGF-II expression is regulated by prolactin. In addition, when IGF-I expression is normal and IGF-II expression is inhibited, overall growth and mammary cell differentiation is inhibited in mice (Brisken et al., 2002). This may indicate a greater role of IGF-II rather than IGF-I in mammary cell proliferation and preparation for lactation onset (Auchtung et al., 2005). Like the previous studies that supplemented lactating cows with melatonin to mimic short-days with variable success, supplementing dry cows exposed to long-days with melatonin did not result in reduced milk production post-calving, indicating other photoperiod mediators impact milk production besides melatonin (Ponchon et al., 2017; Lacasse et al., 2014).

Given the effects of photoperiod during the dry period on subsequent milk production, Morin and colleagues examined whether there were any effects on colostrum production as well (Morin et al., 2001). However, they found no effects on colostral IgG concentration or volume of colostrum produced for cows exposed to long days or short days for either the entire dry period or the 21 days immediately prior to calving.

COMPONENTS OF THE CALF IMMUNE SYSTEM

Achieving optimum colostrum quality and quantity is critical for calf health. The components of colostrum previously described each play a unique role in providing the calf with nutrients for growth as well as effective immune system. Immune system responses are broken into innate and adaptive responses (Delves and Roitt, 2000). The innate immune system is comprised of phagocytic cells (including neutrophils, monocytes and macrophages), cells that release inflammatory mediators (including basophils, mast cells and eosinophils) and natural killer cells. The adaptive immune response utilizes B and T cells, which are antigen specific. Antigens refer to any foreign substance which induces an immune response in the body (Davies and Padlan, 1990). All cells of the immune system develop from stem cells in the liver and bone marrow before entering extracellular fluid (Delves and Roitt, 2000). Complement proteins and cytokines also aid in both innate and adaptive immune processes.

Immune Development - Immune system development begins as early as 6 weeks of gestational life in calves (Schultz et al., 1973). The thymus develops at 42 days of gestation and the spleen can be identified at 55 days of gestation (Schultz et al., 1973). The thymus is critical for the development of lymphocytes, which have a critical role in immune function (Thapa and Farber, 2019). The spleen acts as a filter to remove phagocytic bacteria from the bloodstream and is responsible for producing antibodies (Bohnsack and Brown, 1986). IgG antibodies can be detected at 145 days of gestation, while IgM antibodies can be detected as early as 45 days (Schultz et al., 1973).

Due to the limit of maternal antibody transfer to the fetus by the placenta, the calf relies on the innate immune system and maternal antibodies from colostrum for immune protection (Tizard, 2017). At birth, calves have high numbers of phagocytic cells, however, their function is 50% less than calves that are 16 weeks of age (Hauser et al., 1986). In addition, complement proteins are only 12-60% of adult levels at birth (Renshaw et al., 1978). T cells do not reach peak numbers until 8 months of age (Hein, 1994). Corticosteroid release during calving disrupts the newborn immune response and reduces cytokine production and lymphocyte response to pathogens (Cortese, 2009). These markers of immune function reach their lowest levels around 3 days after birth, before beginning to increase, leaving the < 3-day old calf extremely susceptible to pathogens (Cortese, 2009).

However, colostrum is rich in immunoglobulins, T cells, B cells, macrophages, neutrophils and leukocytes which aid in developing the calf’s immune system (Cortese, 2009). At birth, the small intestine is lined with epithelial cells that nonselectively absorb several types of molecules, including colostral proteins via pinocytosis (Cortese, 2009). Immunoglobulins are then transported into the lymphatic system and later, the circulatory system (Weaver et al., 2000). As soon as the digestive tract is stimulated with feedstuffs, the epithelial cell population becomes exhausted and is replaced by a more mature epithelial cell population that does not permit nonselective absorption via pinocytosis (Cortese, 2009; Smeaton and Simpson-Morgan, 1985). Known as “gut closure”, by 6 h after birth, absorption capacity is only 50%, 33% by 8 h and by 24 h, the gut is “closed” and very little to no absorption capacity is left (Rischen, 1981). If feeding is delayed, gut closure can be extended to 36 h (Stott et al., 1979). Maternal leukocytes can also cross the gastrointestinal epithelium and be detected in the calf's blood (Reber et al., 2005). Calves that received colostrum from dams vaccinated against bovine viral diarrhea virus (BVDV) during the dry period, had leukocytes that responded to BVDV compared to calves that ingested colostrum from dams not vaccinated for BVDV (Donovan et al., 2007).

Factors Affecting Immune Function – Both pre- and postnatal stress can have significant impacts on the calf immune system. Calves born to dams that were heat-stressed during late gestation had less total plasma protein, lower total serum IgG, lower absorption efficiency of immunoglobulins and lower proliferation of peripheral blood mononuclear cells, all factors indicating reduced immune function (Tao et al., 2012; Strong et al., 2015). Postnatal stress such as shipping can also reduce immune function, evidenced by lower blastogenic responses of lymphocytes (Blecha et al., 1984). Pen and groupmate changes can also induce stress and increase calf susceptibility to various pathogens (Wilcox et al., 2013).

Plane of nutrition can modulate immune responses in calves, evidenced by increased neutrophil oxidative burst, increased whole blood killing of *E. coli* and reduced susceptibility to pathogens for calves that were fed a higher fat and protein diet compared to calves fed a lower plane of nutrition (Ballou, 2012). Chromium supplementation has also been shown to increase antibody numbers to bovine infectious rhinotracheitis virus (IBR) after vaccination compared to non-chromium supplemented calves (Burton et al., 1994).

Differences in immune function between Jersey and Holstein calves have been noted, with Jersey calves having reduced immune response when challenged with LPS or

E. coli (Ballou, 2012). These responses can be improved with increased plane of nutrition, but not to the same levels of Holstein calf counterparts. In addition, these results were seen despite Jerseys having greater absorption efficiency of IgG, evidenced by increased total serum protein levels (Ballou, 2012).

As mentioned in previous sections, vaccinating the dam increases the number of specific antibodies in the colostrum, which are transferred and utilized by the calf for immune protection (Smith et al., 2014). Vaccines are also available for newborn calves less than 10 days old, which stimulate antibody production to various pathogens (Woolums et al., 2013; Mahan et al., 2016). Vaccine timing is critical, as presence of antibodies derived from colostrum can inhibit the antibody production by the calf after vaccination (Ellis et al., 2001). However, once maternally derived antibody levels drop, the calf is susceptible to pathogens (Chase et al., 2007). Therefore, vaccinating the calf late enough that maternal antibodies will not interfere with the immune system response, but early enough to provide protection after maternal antibodies have disappeared is the goal. Most maternal antibodies have a half-life of 16 – 28 days, thus, efficacy of vaccines before this period can be reduced (Fulton et al., 2004).

CONCLUSION

Pre-weaned calf management is a costly and time-consuming area of dairy production. Each calf represents a $2,000 investment that will not generate a return on investment until around two years of age, when they enter the lactating cow herd. Therefore, ensuring calf survival while minimizing costs associated with calf management are key goals. Currently, around 19% of calves in the US do not consume adequate quality or quantity colostrum, resulting in death or reduced performance later in life. This translates to $2 billion dollar losses annually from reduced milk production alone, without including the cost of replacement calves, supportive care, or purchase of additional colostrum products. Therefore, identifying methods to improve calf health by improving colostrum production is critical and will save thousands of calves’ lives and billions of dollars for dairy producers.

Evaluating the impact of environmental factors such as photoperiod, temperature, and humidity on colostrum production in dairy cattle will improve our understanding of colostrum synthesis and potentially identify methods to alter and improve colostrum production in dairy cows. Strong evidence exists that colostrum production fluctuates seasonally in both Holstein and Jersey cattle and is directly affected by environmental temperature and humidity. In addition, numerous studies show that altered photoperiod during the dry period impacts milk production post-calving. While only one study has evaluated the direct effect of altered photoperiod on colostrum production and found no differences, there may be differences by breed or a synergistic effect of photoperiod and temperature-humidity that have not yet been elucidated. Studying the effect of these factors on colostrum will improve dry cow management and pre-weaned calf management, which will improve calf survival and calf growth, reproductive performance and milk production later in life.

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CHAPTER 2. EFFECT OF ALTERED PHOTOPERIOD DURING THE DRY PERIOD ON COLOSTRUM AND MILK PRODUCTION IN HOLSTEIN AND JERSEY COWS

Abstract

Little to no research has been conducted on the effect of altered photoperiod during the dry period on colostrum production among dairy cattle breeds. Short day photoperiod (SDPP) is defined as 8 h of continuous light compared to long-day photoperiod (LDPP) consisting of 16 h of light. Multi-parous Holstein cows exposed to SDPP produced up to 3.2 kg more milk per day post-calving when compared to cows exposed to LDPP; it is unknown if a similar response would be observed for Jersey cows. The objective of this study aimed to examine the effect of photoperiod during the dry period on subsequent colostrum and milk production in Holstein and Jersey cattle. Holstein and Jersey cows (n = 33) were dried off 60 d prior to their due date and randomly assigned to SDPP (Holstein (n = 9), Jersey (n = 8)) or LDPP (8 Holstein (n = 8), Jersey (n = 8)) until calving. Cows were weighed at time of enrollment (d 0 weight) and were housed in an enclosed barn at 20°C and exposed to 250 to 450 lux (unit of illuminance) during periods of light and <10 lux during periods of darkness. At calving, colostrum volume was weighed and tested for relative protein concentration with a Brix refractometer and a sample was collected for composition analysis (fat, protein, lactose, solids-not-fat (SNF)) via infrared spectroscopy and immunoglobulin (IgA, IgG, IgG1, IgM), lactoferrin and somatic cell score (SCS) analysis. Post-calving, cows were returned to the free-stall barn and exposed to ambient photoperiod and temperature. Milk production data were collected for 15 weeks post-calving. Data were analyzed using PROC MIXED in SAS

(SAS 9.4; SAS Institute, INC., Cary, NC) with treatment, breed, and d 0 weight as fixed effects. PROC MIXED with repeated measures was used to evaluate the relationship of daylength and breed with mature milk volume, fat, and protein production. Random effects included replicate, lactation number, genetic inbreeding percentage, previous lactation mature equivalent (ME) 305-day protein production and calf sex. For colostrum, total weight, SNF, lactose, lactoferrin, IgG, IgG1 and SCS did not differ by breed or treatment. Brix score, colostral protein, fat, IgA, and IgM were increased in Jersey cows compared to Holstein cows. Post-calving, milk production was increased in Holstein cows compared to Jersey cows but unaffected by photoperiod treatment. Conversely, milk protein percentage was increased for Jersey cows compared to Holstein cows but also unaffected by photoperiod treatment. Milk fat was increased for LDPP Holstein cows compared to SDPP Jersey cows during the first week of lactation, which is likely due to the transition from colostrum to mature milk production. Overall, photoperiod did not affect colostrum production, but differences by breed were detected. Photoperiod during the dry period did not impact mature milk production or protein, but milk fat percentage was affected by photoperiod × breed. Therefore, altered lighting during the dry period does not unfavorable impact colostrum or milk production in Jersey or Holstein cows.

Key Words. Colostrum, photoperiod, dry cow

INTRODUCTION

Calves are born immunoglobulin deficient and must ingest and absorb colostrum containing antibodies for effective immunity (Weaver et al., 2000). Therefore, high quality colostrum, evidenced by containing 50 g/L of IgG, is critical for calf survival and success (Geiger, 2020). However, colostrum volume and quality vary substantially from cow to cow, ranging from 2.8 to 26.5 liters and 13 to 256 g/L of IgG, respectively, making it difficult to ensure every calf receives adequate quantity and quality colostrum (Morin et al., 2001; Conneely et al., 2013; Wells et al., 1996). Despite intensive management for high quality colostrum, upwards of 20% of cows in the US produce colostrum that does not meet the minimum 50 g/L of IgG quality criteria (USDA/NAHMS, 2018). This results in 19% of dairy heifer calves consuming inadequate levels of IgG, which is known as failure of passive transfer (FPT) (Beam et al., 2009). Approximately 16% of FPT calves will die, while those that survive have reduced average daily gain, increased mortality rates and have a 2,607 kg reduction in milk production through their first 2 lactations and thus, lasting effects on farm profitability (Robison et al., 1988; Faber et al., 2005). Due to the prevalence of inadequate colostrum and the negative effects on calf health, cow milk production and profitability, there is a need to determine environmental factors that may contribute to poor colostrum production.

Season of calving may alter colostrum production based on temperature, humidity and(or) photoperiod exposure during the dry period. Jersey cows that calve in June produced 6.5 to 6.6 kg of colostrum. (Gavin et al., 2018). However, Jersey cows calving in December produced only 1.3 kg for multiparous and 4.2 kg for primiparous cows. The temperature humidity index (THI) and photoperiod peripartum were highly correlated with colostrum volume for multiparous and primiparous Jerseys. Colostrum yield was positively correlated with the number of days above 23 °C during the 21 days before calving in Holstein cows. However, IgG was negatively correlated. This is further supported with previous literature showing that increased colostral volume was associated with reduced IgG content (Cabral et al., 2016; Silva-del-Rio et al., 2017).

Photoperiod has direct effects on milk production in Holstein cows. Increasing daylength to 16 to 18 h per day increased milk production by 2.5 kg per day for lactating Holstein cattle (Dahl et al., 2000; Phillips and Schofield, 1989). Conversely, limiting daylength to 8 h per day during the dry period resulted in increased milk production by 3.2 kg per day for up to 16 weeks of lactation, compared to Holsteins exposed to long day photoperiod during the dry period (Miller et al., 2000). Therefore, reduced daylength during the dry period has been adopted by many dairy producers to increase milk production. However, little is known about the effects of photoperiod during the dry period on colostrum production.

Morin et al. (2001) found no effects on colostral IgG concentration or volume of colostrum produced for Holstein cows exposed to long days or short days for either the entire dry period or the 21 days immediately prior to calving. Little to no research has evaluated the effect of photoperiod manipulation independent of temperature and humidity during the dry period, nor has research been conducted comparing the impact of photoperiod on dairy breed colostrum and mature milk production. Therefore, the objective of this research was to determine the impact of photoperiod on colostrum quantity and composition in Holstein and Jersey cattle as well as mature milk production post-calving.

MATERIALS AND METHODS

Animal Management **–** All animal handling and procedures were approved by the Virginia Tech Institutional Animal Care and Use Committee (#19-099). Thirty-three multiparous (2.6 ± 0.1 lactation) cows were enrolled in two replicates (winter 2020 and winter 2021). On d 0, cows were dried off in the morning and then moved to the research room. For the entirety of the dry period, cows were housed in a temperature (20°C) and humidity controlled (60 to 80%), tie-stall barn. Cows were fed a total mixed ration at 3% of their body weight formulated for the far-off (dry off until 21 days before expected calving) and 5% of their body weight for the close-up dry period (21 days before expected calving until calving) at 0700 h and 1500 h. Feed refusals were collected and weighed daily.

Cows were exposed to one of two treatments: short-day photoperiod (SDPP; n = 16) of 8 h of light per day and 16 h of darkness or long-day photoperiod (LDPP; n = 17) of 16 h of light per day and 8 h of darkness. Furthermore, treatments were subdivided among breeds for SDPP Jersey; n = 8 and Holstein; n = 8 and LDPP Jersey; n = 8 and Holstein; n = 9. Cow pairs were enrolled in the study based on treatment so that start dates for each treatment were equally distributed. Fluorescent lighting was used and during the light period, cows were exposed to 250 to 450 lux and less than 10 lux during dark periods which was confirmed with a digital light meter. Mid study, treatment rooms were switched, but individual animals remained on the same treatment to eliminate room as an environmental effect. Calving difficulty scores were recorded, and calves were separated from dams after birth and not allowed to suckle. Within one h of calving, cows were milked out completely, colostrum volume was measured (kg), and a Brix refractometer was used to calculate Brix score of the colostrum (%). Composite colostrum samples were collected using aseptic technique for further analyses. All cows received a calcium bolus after calving and were returned to the farm's group pen for fresh cows within four h of calving. From this point, cows were exposed to ambient photoperiod and temperature.

Colostrum Analysis & Production Data **-** Colostrum samples were refrigerated within 30 min of collection, evaluated for somatic cell count using a Cell Counter (DeLaval, Tumba, Sweden) within 6 h of collection before being transformed to somatic cell score (SCS). One aliquot was frozen in DHIA sample tubes and sent to DHIA (Columbus, OH) for compositional analysis (fat, protein, lactose, solids-not-fat (SNF)) via infrared spectroscopy. A second aliquot was centrifuged at 900 g for 15 min to remove the surface fat and then frozen at -80 °C until analyses. ELISA kits (Bethyl Laboratories; Montgomery, TX) were used to determine colostral immunoglobulin levels (IgA, IgG, IgG1, IgM) and lactoferrin concentration. For ELISA analyses, samples were thawed at room temperature and assayed in duplicate, with an interassay CV < 15%. The concentration of each target protein was calculated from a standard reference curve containing known concentrations of the target protein. Daily milk production, fat content and protein content for each cow was recorded through 15 weeks of lactation via Afimilk (Fitchburg, WI). In addition, average daily temperature-humidity index (THI) was calculated from a local weather station.

***Statistical Analysis* -** Colostrum data (colostrum production, Brix score, protein, fat, lactose, SNF, IgA, IgG, IgG1, IgM and lactoferrin) were analyzed using PROC MIXED in SAS 9.4 (Cary, NC). Transformations were applied as needed to ensure residual normality. Fixed effects included treatment, breed and animal weight at treatment start. Replicate, lactation number, percent inbreeding, 305-day mature equivalent (ME) protein production from the previous lactation and sex of the calf were included as random effects. Milk production, fat content and protein content post-calving were averaged for each week and analyzed using PROC MIXED for repeated measurements. Fixed effects were the same as previously described with the addition of week of lactation. Random effects were the same as previously described. Pearson correlations were determined for all colostrum and milk production parameters. Values are reported as the means and standard errors. Significance was determined at $P \leq 0.05$ and tendencies at $P \leq 0.09$. Post-hoc power analyses were performed to ensure adequate sample size to detect significance ($p < 0.05$; power = 0.80).

RESULTS

Colostrum Measurements – Descriptive statistics of all colostrum measures are reported in Table 2-1. Colostrum volume did not differ by breed ($P = 0.364$) or treatment ($P = 0.905$; Table 2-2), however, colostrum volume was positively correlated with the cows' previous lactation 305-day ME protein production ($r_P = 0.35$; $P = 0.045$) and negatively correlated with Brix score ($r_P = -0.59$; $P < 0.001$), colostral protein ($r_P = -0.59$; $P < 0.001$), IgA ($r_P = -0.43$; $P = 0.012$), IgG ($r_P = -0.42$; $P = 0.016$) and IgG1 ($r_P = -0.39$; $P = 0.026$) but was not correlated with IgM ($P = 0.477$). All phenotypic Pearson correlations are displayed in Table 2-3.

Brix score differed by treatment × breed ($P = 0.016$), with LDPP and SDPP Jersey cows having a higher Brix score by 4.5 to 5% compared to Holstein cows of each treatment. (Figure 2-1). However, Brix score did not differ for Jersey cows by treatment ($P = 0.606$) or for Holstein cows by treatment ($P = 0.539$). Brix score was negatively correlated with previous lactation 305-day ME protein production ($r_p = -0.50$; $P = 0.003$), lactose ($r_p = -0.47$; $P = 0.006$) and tended to be negatively correlated with SNF ($r_p = -0.32$; $P = 0.073$) and inbreeding percentage ($r_p = -0.31$; $P = 0.082$). Brix score was positively correlated with colostral fat ($r_p = 0.65$; $P < 0.001$), protein ($r_p = 0.92$; $P < 0.001$), IgA ($r_p = 0.50$; $P = 0.003$) and IgG ($r_p = 0.53$; $P = 0.034$), tended to be correlated with IgG1 ($r_p = 0.322$; $P = 0.067$) but not correlated with IgM ($P = 0.190$).

Colostral protein differed by treatment × breed ($P = 0.020$) and was 1.80% increased ($P = 0.011$) for long-day Jersey cows compared to long-day Holstein cows and 1.66% increased ($P = 0.019$) for SDPP Jersey cows compared to SDPP Holstein cows. Holstein and Jersey cows did not differ within breed, between treatments for protein content ($P = 0.132$; $P = 0.533$) (Figure 2-2). Colostral protein was negatively correlated with previous lactation 305-day mature equivalent protein production ($r_p = -0.47$; $P = 0.006$), SNF ($r_p = -0.43$; $P = 0.012$) and lactose ($r_p = -0.60$; $P < 0.001$).

Colostral fat differed ($P = 0.014$) by breed, but not by treatment ($P = 0.530$) Jersey cows averaging a 0.82% increased fat percentage compared to Holstein cows (Figure 2-3). Colostral fat tended to be negatively correlated with previous lactation 305-day ME protein production ($r_p = -0.33$; $P = 0.059$) and was also negatively correlated with other SNF ($r_p = -0.52$; $P = 0.002$) and lactose ($r_p = -0.57$; $P < 0.001$). Colostral fat was positively correlated with protein ($r_p = 0.60$; $P < 0.001$).

IgG and IgG1 did not differ by breed or treatment (P > 0.100), however, the percentage of IgG that is IgG1 differed by treatment (P = 0.041), with SDPP cows having a greater IgG1 percentage compared to LDPP cows (Figure 2-6). In addition, IgG was positively correlated with colostral protein (r_P = 0.39; P = 0.024) and Brix score (r_P = 0.37; P = 0.034) and tended to be positively correlated with lactoferrin (r_P = 0.33; P = 0.063). IgG was negatively correlated with colostrum volume (r = -0.42; P = 0.016). IgG1 was positively correlated with protein (r = 0.35; P = 0.049) and tended to be positively correlated with Brix score (r_P = 0.32; P = 0.067). IgG1 was negatively correlated with colostrum volume (r_P = -0.39; P = 0.026). IgG and IgG1 were strongly correlated (r_P = 0.77; P < 0.001).

IgA differed by treatment × breed (P =0.006) with Jersey cows from both treatments having 1.35 to 1.73 g/L increased (P = 0.035; P = 0.001) IgA compared to LDPP Holstein cows, which tended (P = 0.075) to be 1.83 g/L greater than SDPP Holstein cows (Figure 2-4). IgA was negatively correlated with lactose (r_P = -0.53; P = 0.002), percent inbreeding (r_P = -0.39; P = 0.026), SNF (r_P = -0.38; P = 0.031) and tended to be negatively correlated with previous lactation 305-day mature equivalent protein production (r_P = -0.30; P = 0.86). IgA was positively correlated with IgM (r_P = 0.50; P = 0.003), IgG (r_P = 0.43; P = 0.012), colostral protein (r = 0.55; P = 0.001) and colostral fat (r_P = 0.42; P = 0.016).

IgM differed by treatment × breed (P = 0.004) with long-day Holstein cows having the least IgM content compared to SDPP Holstein cows (P = 0.018) and the LDPP Jersey cows (P = 0.001) (Figure 2-5). SDPP Holstein cows and SDPP Jersey cows did not differ (P = 1.000) in their IgM content. LDPP Jersey cows had increased IgM compared to SDPP Jersey cows ($P = 0.007$) and LDPP Holstein cows ($P = 0.001$) but did not differ ($P = 1.000$) from SDPP Holstein cow IgM content. IgM was negatively correlated with inbreeding percentage ($r_P = -0.36$; $P = 0.04$) and tended to be negatively correlated with previous lactation 305-day ME protein production ($r_P = -0.30$; $P = 0.09$).

Milk Production Measurements – Milk production by week of lactation was greater ($P < 0.001$) for Holstein cows by 18.9 and 18.0 kg during week 4 and 6 of lactation, shown in Figure 2-7. Milk production did not differ ($P = 1.000$) between treatments or by breed × treatment. Milk protein percentage by week of lactation was greater ($P = 0.016$) for Jersey cows during week 2 through 9 and week 12 and 15 of lactation compared to Holstein cows (Figure 2-8). No difference ($P = 1.000$) in milk protein percentage between treatments or by breed × treatment was detected. Milk fat percentage by week of lactation differed ($P < 0.001$) by breed × treatment for the first week of lactation. (Figure 2-9). LDPP Holstein cows had the greatest milk fat percentage and SDPP Jersey cows had the least milk fat percentage. Long-day photoperiod Jersey cows and SDPP Holstein cows were intermediate and not different from the other treatment groups.

DISCUSSION

This is the first known study to evaluate the effect of photoperiod during the dry period on colostrum and milk production in both Holstein and Jersey cows. Based on these results, I suggest no differences in colostrum volume or components due to photoperiod manipulation exist. These results were supported by Morin et al. (2001) who showed that colostrum volume and IgG were not impacted by photoperiod in Holstein cows. However, reported differences in colostrum production across seasons in Holstein and Jersey cattle are not fully understood (Gavin et al., 2018; Cabral et al., 2016). Unlike previous research, cows in this study were housed in an environment in which the temperature and humidity were controlled and held constant at 20 °C and 60 to 80%, respectively. This removed any interaction between THI and photoperiod. Therefore, in an ambient environment, it is possible that an interaction between THI and photoperiod may exist and explain seasonal differences noted in previous colostrum research.

Differences in colostrum volume and components by breed contribute to a growing body of conflicting evidence. No differences in colostrum volume by breed were detected, however the average colostrum volume for each breed was greater than previously observed in literature. Holsteins in this study averaged 11.7 kg, while numerous other studies found an average of 6.1 to 7.0 kg for Holsteins (Zarei et al., 2017; Kehoe et al., 2011; Soufleri et al., 2021). Jerseys averaged 7.0 kg while literature shows an average of 4.0 to 4.3 kg of colostrum (Silva-del-Rio et al., 2017; Gavin et al., 2018; Valldecabres and Silva-del-Rio, 2022). While colostrum volume was elevated, these values were still within the range of values (30.4 kg) in Holstein cows for first milking post-calving (Morin et al., 2001). In addition, increased colostrum volume found here may be due to manual machine milking that was not equipped with an automatic take off or flow sensor system, leading to greater milk evacuation compared to other studies (Krawczel et al., 2017). Additionally, herd genetics used represent the upper range population of cows for colostrum volume. Despite this, cows were enrolled in pairs for respective treatments to account for any differences in milking procedures or herd genetics.

Colostrum components fat (%), protein (%) and SNF (%) were decreased for both breeds compared to previous literature. Colostrum fat content has been reported to range from 4.60 to 6.40%, 17.80 to 18.50% for protein content and 20.28 to 27.20% for SNF content in Holstein cows (Zarei et al., 2017; Soufleri et al., 2021). However, values in this study were 3.09% fat, 9.29% protein and 11.02% SNF for Holstein colostrum. Jersey colostrum has been reported at 5.80% fat content, 22.60% protein content and 23.34 to 31.30% SNF content, whereas this study found 3.09% fat, 9.29% protein and 11.02% SNF in Jersey colostrum (Quigley et al., 1994, Valldecabres and Silva, 2022). The lower values presented in this study are likely due to a dilution effect. Both breeds of cows produced a greater colostrum volume than previously reported, which dilutes and reduces the percentage of various solids content in the colostrum.

Interestingly, lactose content for both breeds (1.86% for Holstein cows, 1.73% for Jersey cows) was similar compared to previous reports (2.00 to 2.20% for Holstein cows, 1.20% for Jersey cows) and was not found to be correlated with colostrum volume in this study. Lactose regulates water and osmotic content in milk by causing water to move from the cytoplasm of mammary epithelial cells into the mammary secretory vesicles and lumen, resulting in increased fluid milk volume (Jenness, 1985; Kuhn et al., 1980). The findings in this study contradict the direct relationship between lactose and volume in mature milk but agrees with Parrish and colleagues who also found no association of lactose with colostrum volume (Parrish et al., 1950).

Lactoferrin binds to iron and is theorized to present anti-microbial and anti-inflammatory mechanisms within the mammary gland and fluid (Ochoa and Cleary, 2009). Increased lactoferrin content reduces bacterial content of colostrum and is beneficial to newborn calf health (Puppel et al., 2020). Like lactoferrin, somatic cells also combat microbes and inflammation and while indicative of an infection, can also be beneficial to calf health when ingested and absorbed (Reber et al., 2005). However, neither lactoferrin nor SCS differed by breed or treatment, indicating little difference to calf immune function based on bacteria load.

Brix score indirectly measures immunoglobulin content by measuring the total solids content of colostrum (Moore et al., 2009). Therefore, the finding that Brix score was greater for Jersey cows than Holstein cows along with greater protein and fat in Jersey cow colostrum agrees with this relationship. Immunoglobulin A and IgM were also greater for Jersey cow colostrum, which contributes to the increased Brix score for the Jersey cows compared to Holstein cows. However, no differences in IgG or IgG1 were detected between breeds.

It is important to note that the Brix refractometer correctly identified 70% of the colostrum samples as adequate (> 50 g/L IgG) or poor (< 50 g/L IgG) as determined by ELISA. Previous studies showed a wide range in correlation (0.43 to 0.73) between Brix score and IgG content as determined by laboratory testing (Lemberskiy-Kuzin et al., 2019; Bielmann et al., 2010). The low correlation between Brix score and IgG content of 0.37 in this study implicates the Brix refractometer as a poor tool to estimate colostrum quality. Were the Brix score used to determine whether dam colostrum should be fed to the calf, such as on a typical dairy operation, 30% of the colostrum collected would have been inadequate quality and fed to the calves, or would have been of adequate quality, but discarded based on the Brix score assessment. The Brix refractometer is less fragile and varies less with differences in colostrum temperature than the colostrometer (Bielmann et al., 2010), however, the colostrometer has a slightly stronger correlation (0.58 to 0.77) with IgG content and may be a better tool for on farm colostrum quality estimates (Bartier et al., 2015; Lemberskiy-Kuzin et al., 2019). Additional testing to evaluate ability of the Brix refractometer and colostrometer to determine IgG content under a variety of conditions is warranted.

This study's findings regarding the lack of Ig differences between breeds was expected as previous literature has reported varying results in dairy cow colostrum immunoglobulin content (Muller and Ellinger, 1981; Hassan et al., 2020; Morrill et al., 2015; Coleman et al., 2015; Morrill et al., 2012; Costa et al., 2021). These discrepancies may be due in part to the method chosen to analyze Ig content. When colostrum has been analyzed by ELISA, a weak correlation (0.36) was reported for IgG values compared to radial immunodiffusion (RID) assay (Gelsinger et al., 2015). This was further supported by Dunn et al. (2018) who compared IgG levels by RID with ELISA and found that RID values were almost doubled. Because very few studies evaluate Ig values in Holsteins and Jerseys directly, it is difficult to ascertain the true comparison of Holstein cows to Jersey cows regarding Ig levels. Immunoglobulin G content of 55% of the cows on this study was below 50 g/L but did not differ by breed or treatment. This suggests that there are significant opportunities to improve Ig production at the herd level and (or) national level.

Interestingly, only IgA and IgM differed between breeds. Both are produced in different locations and utilize a different mechanism to enter the mammary gland than IgG and IgG1. Whereas IgG1 is produced in the spleen and lymph nodes and then selectively transported by binding to Fc receptors on alveolar epithelial cells, IgA and IgM are produced locally in the mammary gland, and then transported across mammary epithelial cells into the mammary gland via the polymeric immunoglobulin receptor

(Butler, 1983; Ahmann et al., 2021; Brandtzaet, 2010; Mostov and Kaetzel, 1999). This may indicate differences in polymeric immunoglobulin receptor number or sensitivity by breed.

Milk production post-calving was not affected by photoperiod treatment and differed between breeds only during weeks 4 and 6 of lactation, with increased milk production from Holstein cows. I expected milk production to be greater for SDPP cows compared to LDPP cows for both breeds based on previous research (Miller et al., 2000; Auchtung et al., 2005; Lacasse et al., 2014; Crawford et al., 2015). However, the discrepancy is likely due to the daily photoperiod that cows were exposed to post-calving once treatmend had ended. Previous studies that found an increase in milk production post-calving for SDPP cows, exposed cows to either ambient photoperiod or LDPP immediately post-calving for the entire study period, for a range in daily light exposure of 9.5 to 16 h per day. In the present study, daily lighting was not ambient photoperiod, nor did it follow a regular pattern. Due to other research project needs, continual (24 h) lighting was utilized sporadically, and daily light exposure ranged from 8 h to 24 h. When cows are exposed to continual light, they lose normal circadian rhythm and exhibit physiological responses like animals exposed to SDPP, which would explain the lack of difference in milk production between photoperiod groups (Dahl et al., 2000).

Milk protein percentage post-calving differed only by breed and was higher for Jersey cows for the majority of the first 15 weeks of lactation. This agrees with previous literature indicating increased protein content for Jersey cows compared to Holstein cows (Cerbulis and Farrell, 1975) and indicates that photoperiod treatment had little to no effect on colostrum protein percentage, moreover, any potential effect was negated by the inconsistent lighting scheme post-calving. Previous literature evaluating milk composition post-calving in response to altered photoperiod during the dry period also did not see any differences in milk protein (Dahl, 2000). Milk fat percentage differed only during the first week post-calving by breed and treatment. Increased fat percentage from Jersey cows would be expected based on breed differences and the dilution effect, however, the greatest protein percentage was exhibited by LDPP Holsteins and the least by SDPP Jersey cows. Because differences were detected only during the first week of lactation, it is likely that transition milk from Holstein cows did not follow predicted patterns due to rapid changes in the mammary gland as the demand for milk volume increased.

Though not measured in the present study, prolactin receptor mRNA expression in the mammary gland of dry cows and circulating IGF-I in lactating cows would be valuable measurements to characterize the effect of altered photoperiod on colostrum and milk production between breeds. Prolactin receptor mRNA expression in the mammary gland is increased in cows exposed to SDPP and circulating prolactin is decreased (Auchtung et al., 2005). This dynamic is thought to sensitize prolactin receptors, allowing for a greater response once circulating prolactin rises at calving and resulting in increased milk production post-calving (Auchtung et al., 2005). This mechanism has only been explored in Holstein cattle and data on Jersey cows would be valuable to determine whether Jersey cows respond similarly to altered photoperiod during the dry period and whether altered lighting was effective. In addition, IGF-I is increased in lactating cows exposed to LDPP and thought to be the driving force behind increased milk production in these animals (Dahl et al., 1997). Measuring IGF-I in this study in both breeds would confirm that the aberrant lighting schedule post-calving did not result in a sustained increase in circulating IGF-I and therefore, the lack of increased milk-production in SDPP cows.

CONCLUSION

Altered photoperiod during the dry period did not affect colostrum volume or components in Holstein or Jersey cattle. Jersey cows produced colostrum with increased Brix score, colostral protein, colostral fat, IgA and IgM content compared to Holstein cows. Altered photoperiod did not affect milk production post-calving, likely due to an aberrant daily lighting scheme. Milk protein percentage post-calving was increased for Jersey cows, as expected, however, milk fat percentage did not follow the same pattern for the first week post-calving and was highest for SDPP Holstein cows. Finally, Brix score may not be a reliable indicator of colostrum quality on-farm and other tools to estimate colostrum Ig content are needed. In conclusion, photoperiod alone did not affect colostrum production and may not account for seasonal differences in colostrum production. Future studies should incorporate THI into experimental designs to tease out interrelationships with photoperiod.

TABLES AND FIGURES

Table 2-1: Descriptive statistics of treatments and colostrum parameters by breed.

	Jersey (n = 16)			Holstein (n = 17)		
Variable	Mean ± SE	Min	Max	Mean ± SE	Min	Max
Lactation Number	3 ± 0	2	4	2 ± 0	2	4
Treatment Length (days)	66 ± 1	58	73	56 ± 2	49	64
Colostrum (kg)[1]	7.0 ± 1.1	3.2	17.9	11.7 ± 1.4	3.8	23.6
Brix Score (%)[2]	28 ± 0	23	32	23 ± 0	19	28
Fat (%)[3]	3.09 ± 0.25	1.75	4.99	2.27 ± 0.22	0.75	3.57
Protein (%)[3]	9.29 ± 0.30	7.38	12.07	7.58 ± 0.30	5.79	9.62
Solids-not-fat (%)[3]	2.84 ± 0.05	2.52	3.40	2.90 ± 0.04	2.58	3.13
SCS[4]	5.66 ± 0.44	2.70	8.10	5.21 ± 0.40	0.60	7.10
Lactose (%)[3]	1.73 ± 0.07	1.38	2.49	1.86 ± 0.05	1.44	2.15
Lactoferrin (g/L)[5]	1 ± 0	0	4	2 ± 0	0	3
IgA (g/L)[5]	6 ± 1	2	12	3 ± 1	1	10
IgG (g/L)[5]	57 ± 4	35	97	65 ± 7	34	129
IgG 1 (g/L)[5]	40 ± 2	20	51	44 ± 2	28	72
IgM (g/L)[5]	12 ± 1	4	21	8 ± 1	5	15

Descriptive statistics were determined using the MEANS procedure of SAS 9.4 (SAS Institute, Inc., Cary, NC)

[1] Colostrum volume determined at first milking post-calving (within one h of calving). Cows were milked completely and colostrum volume was measured on a scale (kg).

[2] Brix score was determined with an optical Brix refractometer at the first milking post-calving (within one h of calving). A composite sample of colostrum was collected aseptically and placed on the Brix face.

[3] Fat (%), protein (%), SNF (%) and lactose (%) were determined by DHIA laboratory via infrared spectroscopy. Composite colostrum samples were collected aseptically at the first milking post-calving (within one h of calving) into 50 mL conical tubes with additive. Samples were frozen within 6 h before being shipped on ice to DHIA.

[4] SCS was determined from a colostrum sample collected aseptically at the first milking post-calving (within one h of calving) and refrigerated within 30 min of collection. SCC was determined using a Cell Counter (DeLaval, Tumba, Sweden). Data were transformed from SCC to SCS using the formula: $SCS = \log_2(SCC/100{,}000) + 3$.

[5] Lactoferrin, IgA, IgG, IgG 1 and IgM were determined via ELISA. A composite colostrum sample was collected at the first milking post-calving (within one h of calving) and refrigerated within 30 min. Samples were centrifuged at 900 g for 15 min and surface fat was removed. Samples were frozen at -80 °C until analyses. ELISA kits (Bethyl Laboratories; Montgomery, TX) were used. Samples were assayed in duplicate with an interassay CV < 15%.

Table 2-2: Average, standard error and *P*-values by breed and treatment group for variables that did not differ by breed or treatment group.

	Short-day Photoperiod		Long-day Photoperiod		*P*-value	
	Jersey	Holstein	Jersey	Holstein	Breed	TRT
Colostrum Volume (kg)[1]	6.0 ± 0.7	12.0 ± 1.6	8.0 ± 2.0	11.3 ± 2.5	0.364	0.905
Solids-not-fat (%)[2]	2.85 ± 0.05	2.87 ± 0.04	2.83 ± 0.10	2.92 ± 0.07	0.727	0.890
Lactose (%)[2]	1.88 ± 0.09	1.84 ± 0.04	1.76 ± 0.12	1.70 ± 0.07	0.289	0.690
Lactoferrin (g/L)[3]	1 ± 0	1 ± 0	1 ± 1	2 ± 0	0.218	0.839
IgG (g/L)[3]	53 ± 4	57 ± 8	61 ± 8	73 ± 12	0.567	0.219
IgG 1 (g/L)[3]	40 ± 3	43 ± 2	40 ± 4	46 ± 5	0.854	0.910
SCS[4]	6.26 ± 0.66	5.48 ± 0.29	5.17 ± 0.57	4.90 ± 0.81	0.208	0.308

Differences by treatment and breed were determined using the MIXED procedure of SAS 9.4 (SAS Institute, Inc., Cary, NC) with fixed effects of treatment, breed and d 0 weight and random effects of replicate, lactation number, genetic inbreeding percentage, previous lactation mature equivalent (ME) 305-d protein production and calf sex.

[1] Colostrum volume determined at first milking post-calving (within one h of calving). Cows were milked completely and colostrum volume was measured on a scale (kg).

[2] SNF (%) and lactose (%) were determined by DHIA laboratory via infrared spectroscopy. Composite colostrum samples were collected aseptically at the first milking post-calving (within one h of calving) into 50 mL conical tubes with additive. Samples were frozen within 6 h before being shipped on ice to DHIA.

[3] IgG and IgG 1 were determined via ELISA. A composite colostrum sample was collected at the first milking post-calving (within one h of calving) and refrigerated within 30 min. Samples were centrifuged at 900 g for 15 min and surface fat was removed. Samples were frozen at -80 °C until analyses. ELISA kits (Bethyl Laboratories; Montgomery, TX) were used. Samples were assayed in duplicate with an interassay CV < 15%.

[4] SCS was determined from a colostrum sample collected aseptically at the first milking post-calving (within one h of calving) and refrigerated within 30 min of collection. SCC was determined using a Cell Counter (DeLaval, Tumba, Sweden). Data were transformed from SCC to SCS using the formula: $SCS = \log_2(SCC/100,000) + 3.4$[5]Lactoferrin,

Table 2-3: Correlation for colostrum parameters with Pearson correlation coefficient value on top and corresponding *P*-value below.

Variables	Inbred[1]	ME Protein[2]	Volume[3]	Brix[4]	Fat[5]	Protein[5]	SNF[5]	SCS[6]	Lactose[5]	Lactoferrin[7]	IgA[7]	IgG[7]	IgG1[7]	IgM[7]
Inbred	-	-0.01[8] 0.979[9]	0.18 0.314	-0.31 0.082	-0.13 0.463	-0.25 0.157	-0.01 0.936	-0.04 0.838	0.14 0.436	-0.05 0.751	-0.39 0.026	-0.18 0.315	-0.13 0.464	-0.36 0.041
MEProtein		-	0.35 0.045	-0.50 0.003	-0.33 0.059	-0.47 0.006	0.24 0.174	-0.10 0.620	0.31 0.077	0.20 0.257	-0.30 0.086	0.06 0.736	0.17 0.337	-0.30 0.085
Volume			-	-0.59 <0.001	-0.22 0.220	-0.59 <0.001	0.136 0.449	-0.12 0.552	0.29 0.100	-0.11 0.541	-0.43 0.012	-0.42 0.016	-0.39 0.026	-0.13 0.477
Brix				-	0.65 <0.001	0.92 <0.001	-0.32 0.073	0.09 0.679	-0.47 0.006	-0.03 0.871	0.50 0.003	0.37 0.034	0.322 0.067	0.234 0.190
Fat					-	0.60 <0.001	-0.52 0.002	0.02 0.935	-0.57 <0.001	-0.23 0.192	0.42 0.016	0.07 0.709	0.07 0.717	0.01 0.958
TP						-	-0.43 0.012	-0.04 0.855	-0.60 <0.001	0.08 0.673	0.55 0.001	0.39 0.024	0.35 0.049	0.27 0.127
SNF							-	0.32 0.123	0.95 <0.001	-0.12 0.506	-0.38 0.031	-0.16 0.377	-0.15 0.404	0.01 0.957
SCS								-	-0.04 0.830	0.19 0.345	0.16 0.434	-0.05 0.797	-0.15 0.47	-0.13 0.517
Lactose									-	-0.08 0.646	-0.53 0.002	-0.25 0.156	-0.24 0.187	-0.15 0.391
Lactoferrin										-	0.23 0.205	0.33 0.063	0.11 0.544	-0.05 0.788
IgA											-	0.43 0.012	0.22 0.228	0.50 0.003
IgG												-	0.77 <0.001	0.18 0.305
IgG1													-	0.12 0.516
IgM														-

Correlations and associated *P*-values were determined using the CORR procedure in SAS 9.4 (SAS Institute, INC., Cary, NC)

[1] Inbreeding percentage of the animal

[2] 305-day mature equivalent protein production for the previous lactation

[3] Colostrum volume determined at first milking post-calving (within one h of calving). Cows were milked completely and colostrum volume was measured on a scale (kg).

[4] Brix score was determined with an optical Brix refractometer at the first milking post-calving (within one h of calving). A composite sample of colostrum was collected aseptically and placed on the Brix face.

[5] Fat (%), protein (%), SNF (%) and lactose (%) were determined by DHIA laboratory via infrared spectroscopy. Composite colostrum samples were collected aseptically at the first milking post-calving (within one h of calving) into 50 mL conical tubes with additive. Samples were frozen within 6 h before being shipped on ice to DHIA.

[6] SCS was determined from a colostrum sample collected aseptically at the first milking post-calving (within one h of calving) and refrigerated within 30 min of collection. SCC was determined using a Cell Counter (DeLaval, Tumba, Sweden). Data were transformed from SCC to SCS using the formula: $SCS = \log_2(SCC/100{,}000) + 3$.

[7] Lactoferrin, IgA, IgG, IgG 1 and IgM were determined via ELISA. A composite colostrum sample was collected at the first milking post-calving (within one h of calving) and refrigerated within 30 min. Samples were centrifuged at 900 g for 15 min and surface fat was removed. Samples were frozen at -80 °C until analyses. ELISA kits (Bethyl Laboratories; Montgomery, TX) were used. Samples were assayed in duplicate with an interassay CV < 15%.

[8] Value depicts correlation coefficient

[9] *P*-value corresponding to correlation coefficient

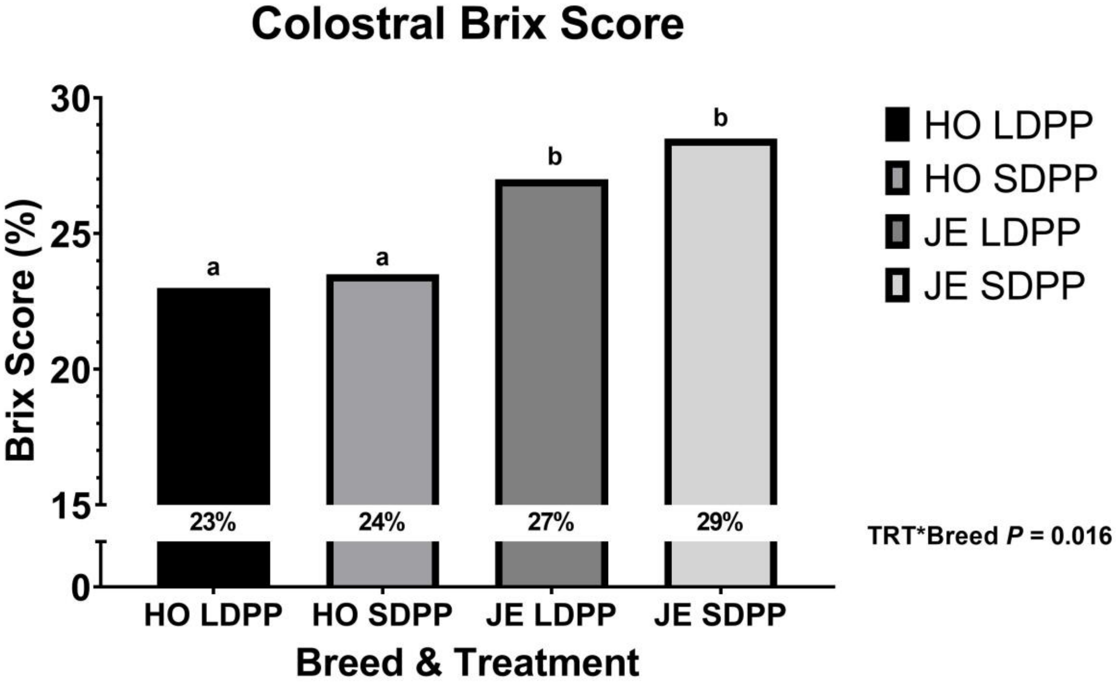

Figure 2-1: Average and SEM colostral Brix score for long-day photoperiod (LDPP) and short-day photoperiod (SDPP) Holstein (HO) and Jersey (JE) cows. Differences determined using SAS 9.4 MIXED procedure with treatment, breed and d 0 weight as fixed effects and replicate, lactation number, genetic inbreeding percentage, previous lactation ME 305-d protein production and calf sex as random effects. Brix score differed by treatment × breed ($P = 0.016$), with Jersey cows in the long-day and short-day treatments having a higher ($P = 0.010$; $P = 0.004$) Brix score. However, Brix score did not differ between treatment groups for the same breed (Holstein, $P = 0.539$; Jersey, $P = 0.608$). Different letters indicate statistically significant differences ($P \leq 0.05$).

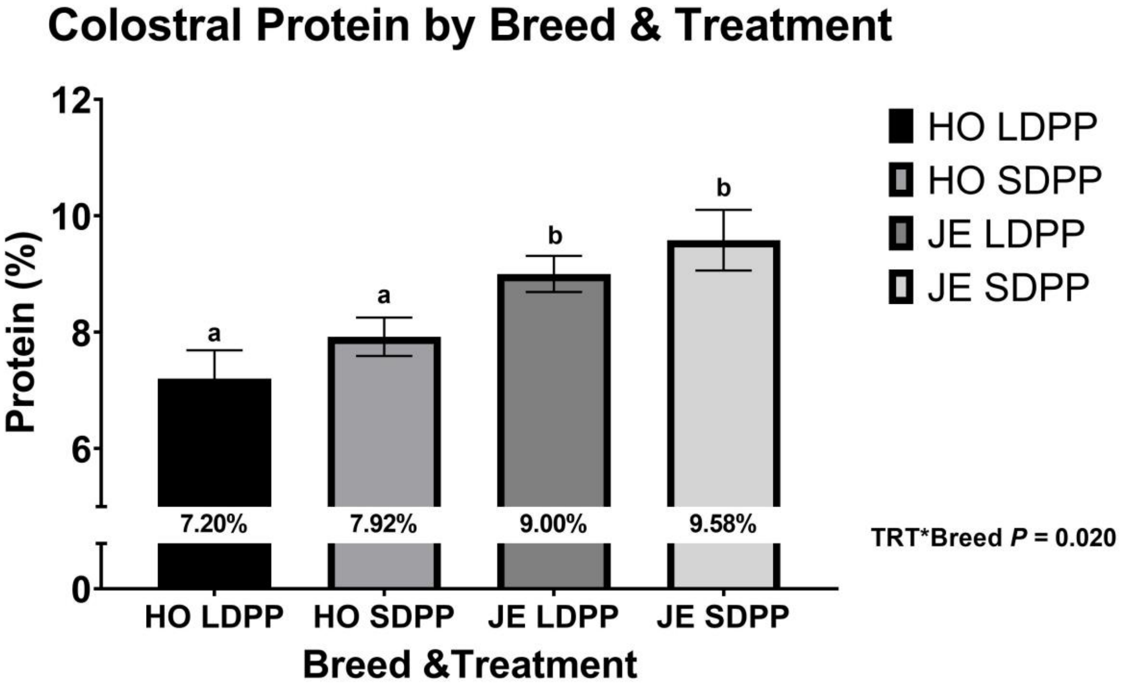

Figure 2-2: Average and SEM colostral protein content for long-day photoperiod (LDPP) and short-day photoperiod (SDPP) Holstein (HO) and Jersey (JE) cows. Differences determined using SAS 9.4 MIXED procedure with treatment, breed and d 0 weight as fixed effects and replicate, lactation number, genetic inbreeding percentage, previous lactation ME 305-d protein production and calf sex as random effects. Protein content differed by treatment × breed ($P = 0.020$) with SDPP and LDPP Jersey cows having increased protein compared to SDPP and LDPP Holstein cows. Protein did not differ between treatment groups for the same breed. Different letters indicate statistically significant differences ($P \leq 0.05$).

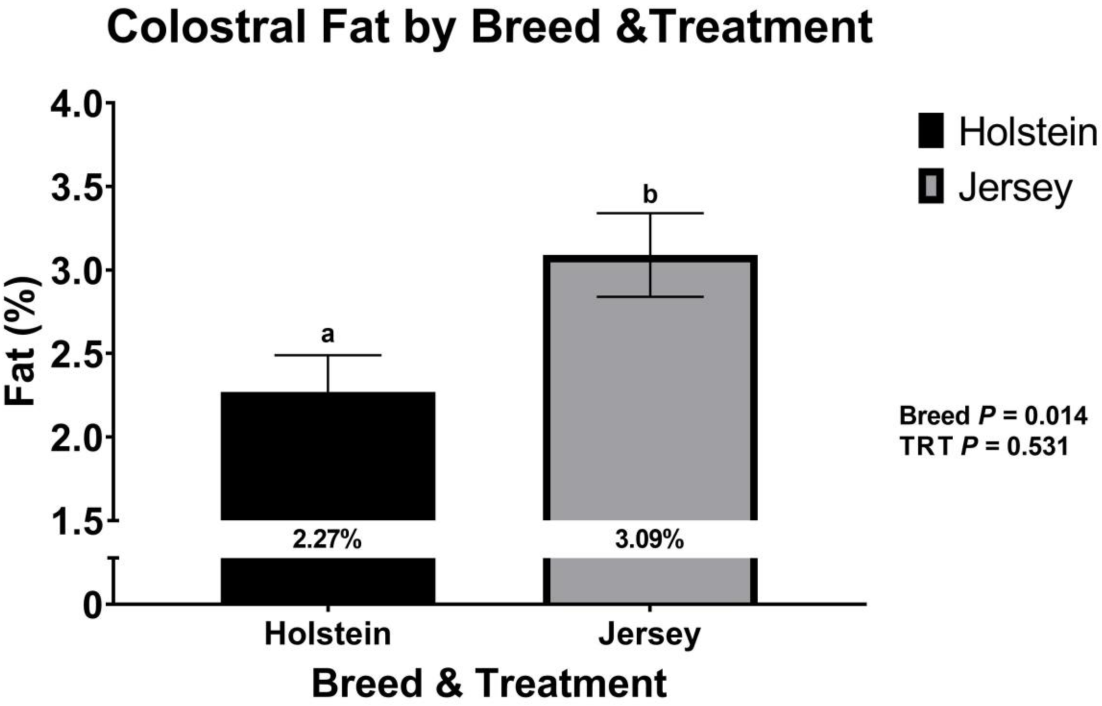

Figure 2-3: Average and SEM colostral fat content for long-day photoperiod (LDPP) and short-day photoperiod (SDPP) Holstein (HO) and Jersey (JE) cows. Differences determined using SAS 9.4 MIXED procedure with treatment, breed and d 0 weight as fixed effects and replicate, lactation number, genetic inbreeding percentage, previous lactation ME 305-d protein production and calf sex as random effects. Fat content differed (P = 0.014) by breed with Jersey cows having increased fat percentage compared to Holstein cows. No differences by treatment (P = 0.531) were detected. Different letters indicate statistically significant differences ($P \leq 0.05$).

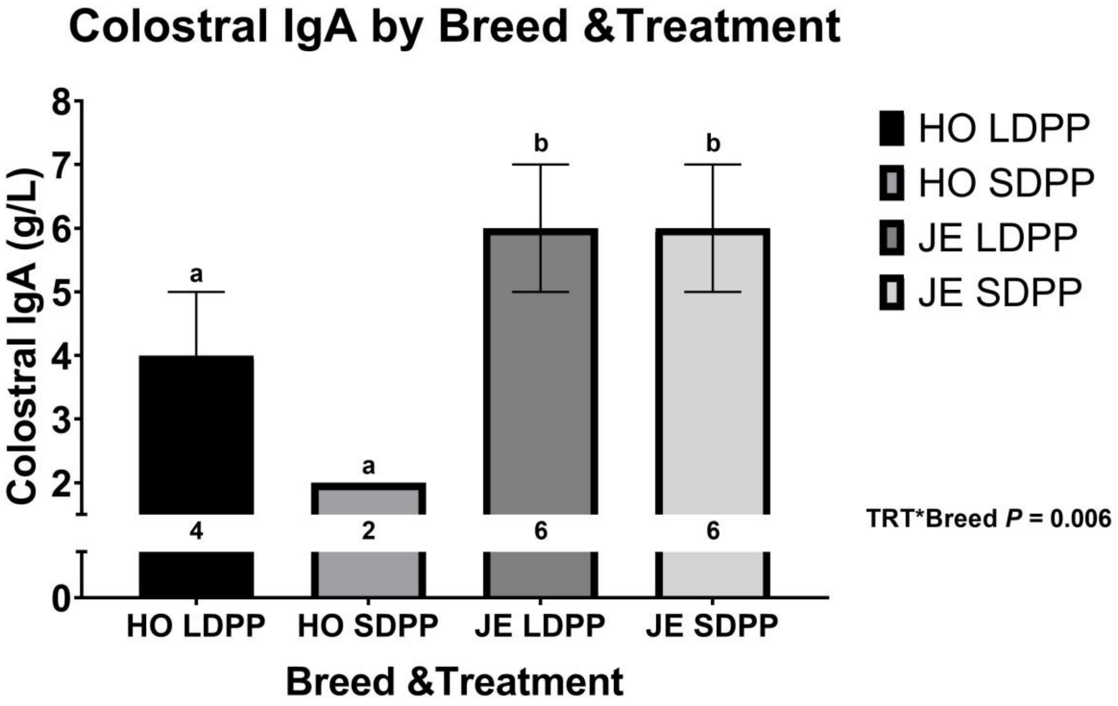

Figure 2-4: Average and SEM colostral immunoglobulin A (IgA) content for long-day photoperiod (LDPP) and short-day photoperiod (SDPP) Holstein (HO) and Jersey (JE) cows. Differences determined using SAS 9.4 MIXED procedure with treatment, breed and d 0 weight as fixed effects and replicate, lactation number, genetic inbreeding percentage, previous lactation ME 305-d protein production and calf sex as random effects. IgA content differed by treatment × breed and was greater for SDPP and LDPP Jersey cows compared to SDPP and LDPP Holstein cows (P = 0.006). IgA did not differ between treatment groups for the same breed. Different letters indicate statistically significant differences ($P \leq 0.05$).

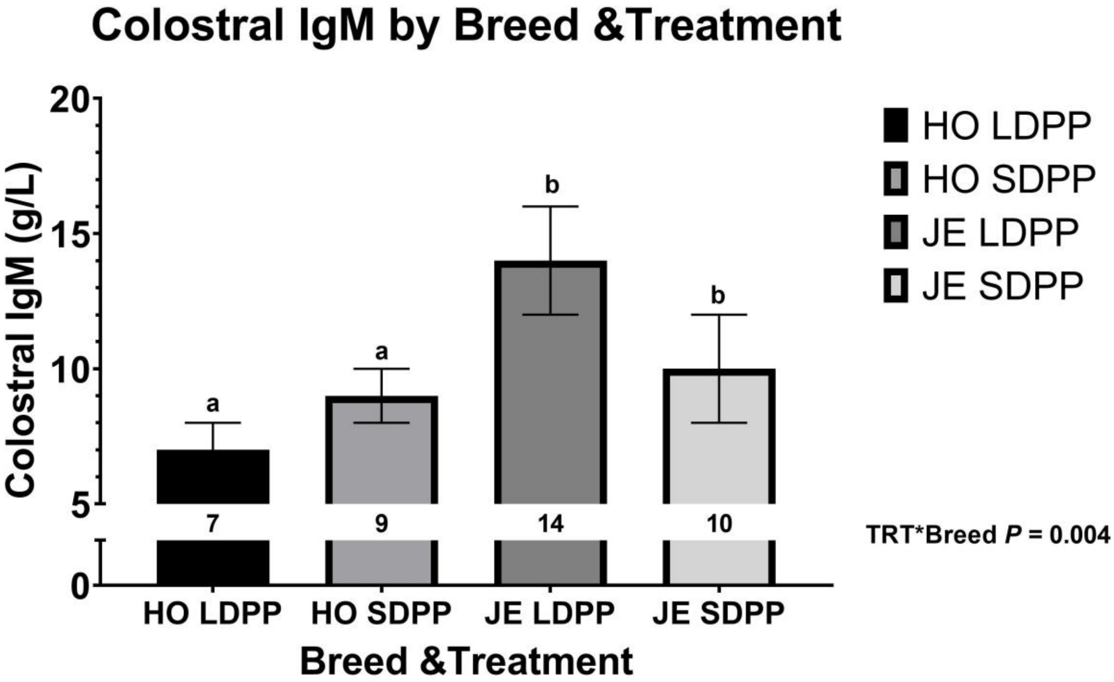

Figure 2-5: Average and SEM colostral immunoglobulin M (IgM) content for long-day photoperiod (LDPP) and short-day photoperiod (SDPP) Holstein (HO) and Jersey (JE) cows. Differences determined using SAS 9.4 MIXED procedure with treatment, breed and d 0 weight as fixed effects and replicate, lactation number, genetic inbreeding percentage, previous lactation ME 305-d protein production and calf sex as random effects. IgM differed by treatment × breed ($P = 0.004$) and was increased for SDPP and LDPP Jersey cows compared to SDPP and LDPP Holstein cows. IgM did not differ between treatment groups for the same breed. Different letters indicate statistically significant differences ($P \leq 0.05$).

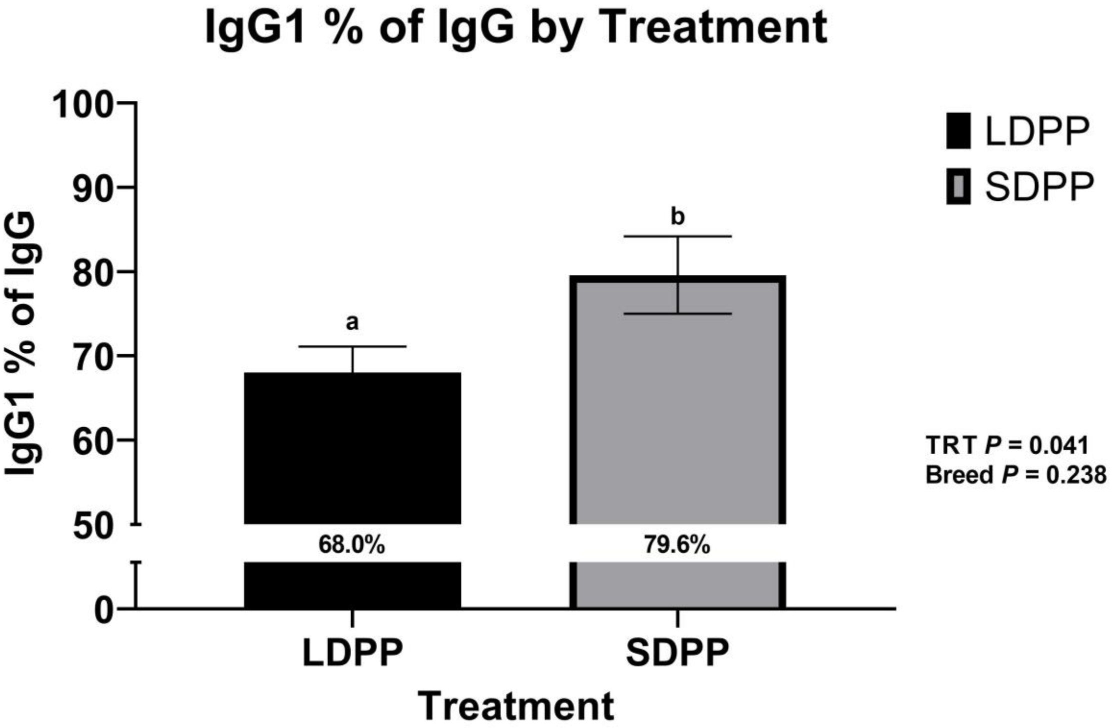

Figure 2-6: Average and SEM colostral percent of immunoglobulin G1 (IgG1) that makes up immunoglobulin G (IgG) for long-day photoperiod (LDPP) and short-day photoperiod (SDPP) cows. Differences determined using SAS 9.4 MIXED procedure with treatment, breed and d 0 weight as fixed effects and replicate, lactation number, genetic inbreeding percentage, previous lactation ME 305-d protein production and calf sex as random effects. IgG1 % of IgG was greater for SDPP cows than LDPP cows ($P = 0.041$), however differences by breed were not detected ($P = 0.238$). Different letters indicate statistically significant differences ($P \leq 0.05$).

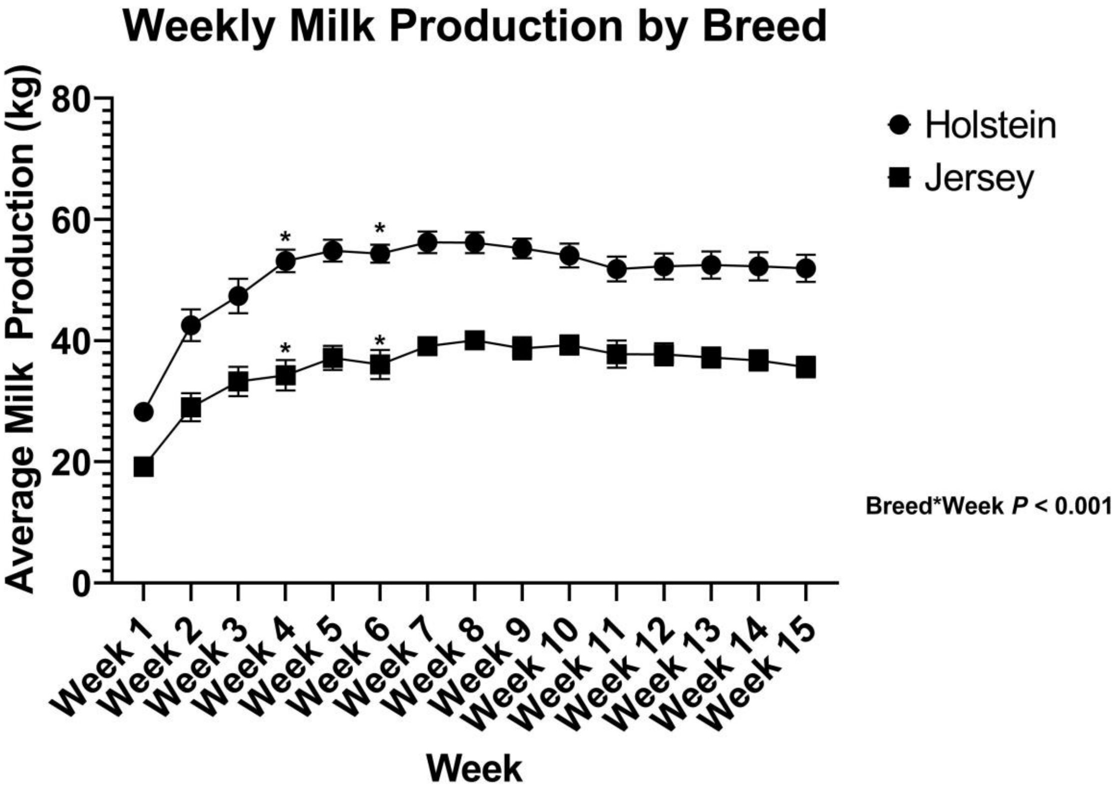

Figure 2-7: Average and SEM weekly milk production post-calving for Holstein and Jersey cows. Differences determined using SAS 9.4 MIXED procedure with treatment, breed and d 0 weight as fixed effects, milk production by week as repeated measure and replicate, lactation number, genetic inbreeding percentage, previous lactation ME 305-d protein production and calf sex as random effects. Milk production differed by breed × week ($P < 0.001$) and was increased for Holstein cows during week 4 and 6 of lactation. Differences by treatment were not detected ($P > 1.000$). Asterisks indicate statistically significant differences ($P \leq 0.05$).

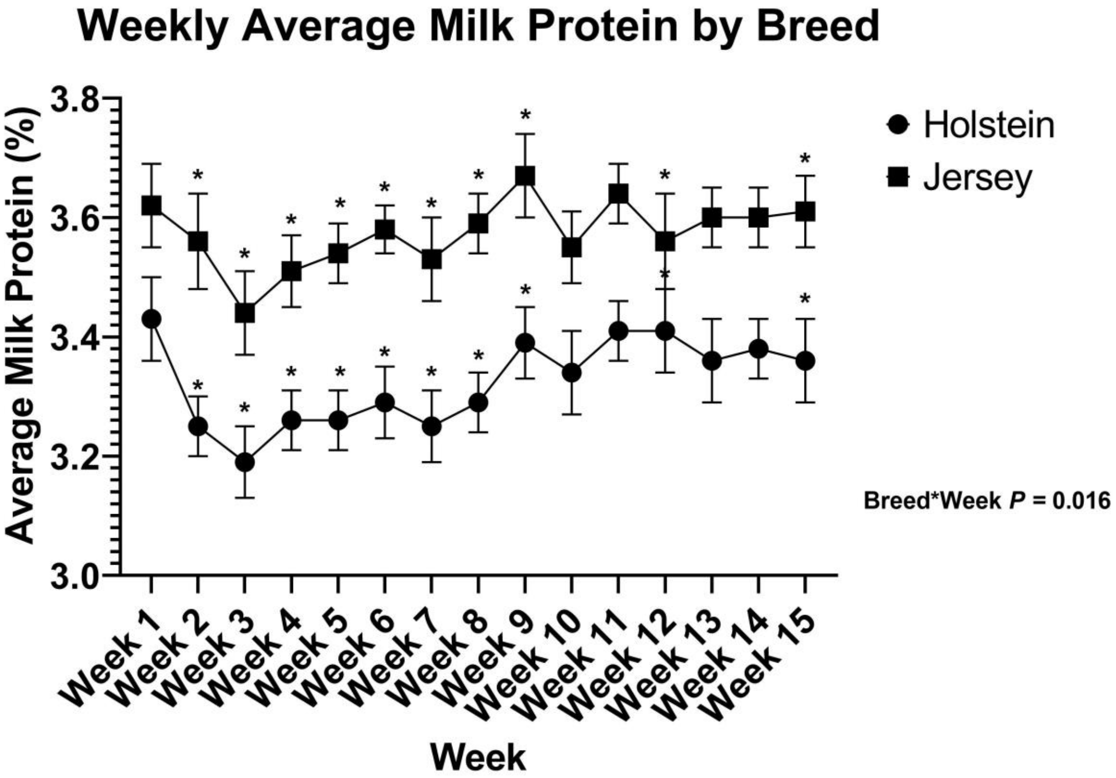

Figure 2-8: Average and SEM weekly milk protein percentage post-calving for Holstein and Jersey cows. Differences determined using SAS 9.4 MIXED procedure with treatment, breed and d 0 weight as fixed effects, milk protein percentage by week as repeated measure and replicate, lactation number, genetic inbreeding percentage, previous lactation ME 305-d protein production and calf sex as random effects. Milk protein percentage differed by breed × week ($P = 0.016$) and was increased for Jersey cows during week 2 through 9, 12 and 15 of lactation. Differences by treatment were not detected ($P > 1.000$). Asterisks indicate statistically significant differences ($P \leq 0.05$).

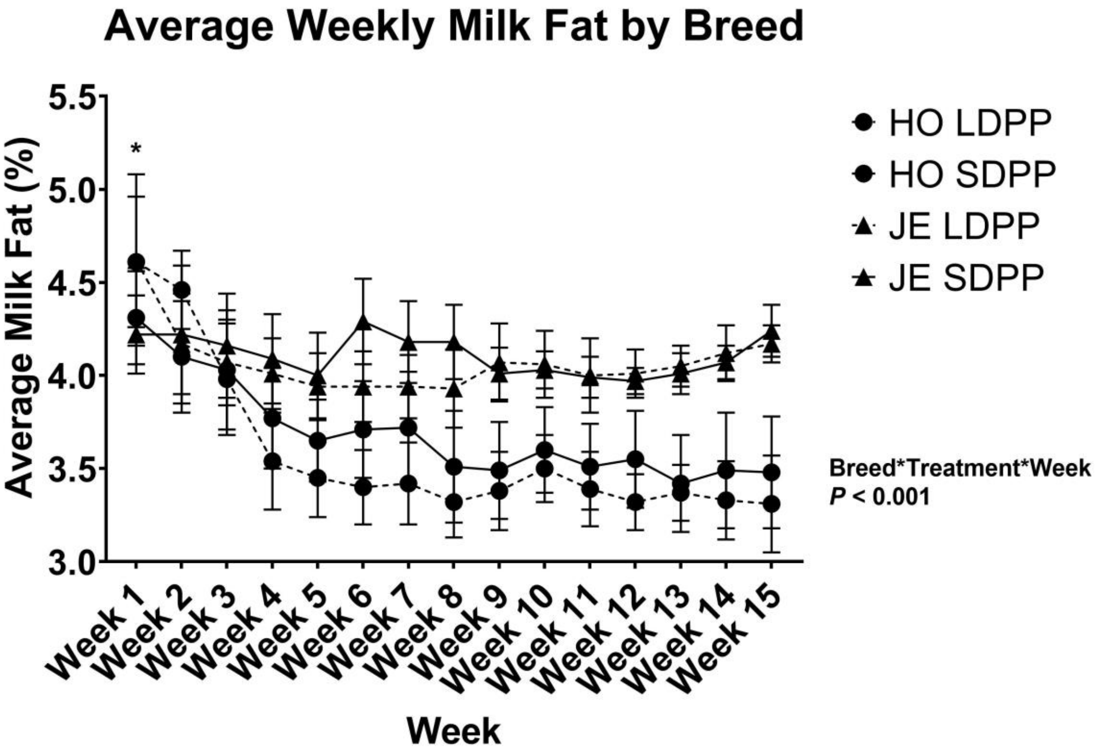

Figure 2-9: Average and SEM weekly milk fat percentage post-calving for Holstein and Jersey long-day photoperiod (LDPP) and short-day photoperiod (SDPP) cows. Differences determined using SAS 9.4 MIXED procedure with treatment, breed and d 0 weight as fixed effects, milk fat percentage by week as repeated measure and replicate, lactation number, genetic inbreeding percentage, previous lactation ME 305-d protein production and calf sex as random effects. Milk fat percentage differed by treatment × breed × week ($P < 0.001$) for the first week of lactation and was increased for LDPP Holstein cows and least for SDPP Jersey cows. Asterisks indicate statistically significant differences ($P \leq 0.05$).

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CHAPTER 3: PHOTOPERIOD AND TEMPERATURE-HUMIDITY INDEX DURING THE DRY PERIOD IMPACT COLOSTRUM PRODUCTION IN HOLSTEIN AND JERSEY CATTLE

Abstract

During winter months, Holstein and Jersey cows have reduced colostrum yield, increased Brix score and increased IgG content in their colostrum. Both termperature-humidity-index (THI) and light intensity are phenotypically correlated with colostrum production, however, it is unknown how these environmental factors interact with colostrogenesis. The objective of this study was to determine the effect of photoperiod and THI during the dry period on subsequent colostrum production in Holstein and Jersey cows. Jersey (n = 89) and Holstein (n = 137) cows were enrolled at calving February 2018 until June 2019 from two farms. Calves were weighed at birth and colostrum volume and Brix score was recorded. For Jersey cows, a sample of colostrum was collected and assayed for fat percentage, protein percentage, lactose percentage, solids-not-fat (SNF) percentage and somatic cell score (SCS) by Dairy Herd Information Association (DHIA) via infrared spectroscopy. Daily maximum THI (mTHI) and daily photoperiod exposure (PHOTO) were collected from weather stations located within 5 km of each farm and averaged for the far-off (FO), close-up (CU) and total dry period. Cows were broken into a top, middle and bottom third based on CU PHOTO exposure: PHOTO 1 – CU PHOTO < 708 mins (n = 54 Holstein; n = 22 Jersey), PHOTO 2 – CU PHOTO 709 – 824 mins (n = 43 Holstein; n = 31 Jersey) and PHOTO 3 – CU PHOTO > 825 mins (n = 43 Holstein; n = 36 Jersey). Statistical analyses were performed using PROC MIXED in SAS 9.4 (SAS Institute, INC., Cary, NC) to determine the effect of PHOTO category on colostrum volume, Brix

score, calf birthweight and colostrum components with fixed effect of breed and random effects included animal, farm, age at calving (yr), dry period length (d), inbreeding percentage, protein production PTA (kg) and CU mTHI. Regression analyses were also used within the GLM procedure to determine relationships of colostrum volume, Bri score, calf birthweight and colostrum components with breed, farm, age at calving (yr), dry period length (d), inbreeding percentage, PTA for protein production, CU mTHI, FO mTHI, FO percent of days THI > 68, CU percent of days THI > 68, FO PHOTO and CU PHOTO. Holstein cows produced more colostrum compared to Jersey cows within each photoperiod category. PHOTO 1 cows produced less colostrum than PHOTO 2 or PHOTO 3 cows. A one-unit change in age of calving (yr), % days of THI > 68 in the FO period and FO photoperiod decreased colostrum volume, but a one-unit change in dry period length and CU photoperiod increased colostrum volume. Despite significance, predicted impacts on colostrum volume were negligible. Within farm, Brix score did not differ by PHOTO category and was not predicted to be affected by THI or photoperiod. Photoperiod category was not associated with colostral components. However, a one-unit change in FO photoperiod length was predicted to increase colostrum protein percentage but decrease colostrum lactose percentage. In turn, both colostrum fat percentage and lactose percentage were positively correlated with colostrum volume. Additionally, a one-unit change in % days of THI > 68 in CU period was predicted to decrease colostral protein and SNF percentage. Both CU photoperiod and THI were moderately correlated with colostrum volume and Brix score. Finally, Brix score was strongly and positively correlated with colostral total protein percentage and SNF percentage. From these data, we suggest that while photoperiod exposure may impact dairy breeds differently for

colostrum volume and Brix percentage, colostrum components were not greatly impacted in Jersey cows. However, protein, SNF and lactose may be affected by both photoperiod and THI. In addition, photoperiod and THI during the close-up period had a greater impact on colostrogenesis, indicating that there may be a greater sensitivity to environmental conditions during the close-up period. Because this study relied on ambient photoperiod and THI, future research is needed to assess the impact of THI gradients on colostrogenesis, independent of photoperiod.

Key Words: Colostrum, photoperiod, temperature-humidity index (THI), dry cow

INRODUCTION

Colostrum production in dairy cattle is influenced by several management and physiological factors, such as age of dam, diet, breed, dry period length, vaccination status and overall health (McGrath et al., 2015). These factors affect both colostrum volume and colostrum quality (i.e., immunoglobulin, protein and fat content (Morin et al., 2001; Conneely et al., 2013; Wells et al., 1996). Immunoglobulin G (IgG) content of 50 g/L has widely been accepted as the minimum industry standard for adequate quality colostrum (Geiger, 2020). Despite close management of factors known to affect colostrum, producers still note differences among cows for colostral volume ranging from 2.8 to 26.5 liters as well as for immunoglobulin content, ranging from 13 to 256 g/L of IgG (Morin et al., 2001; Conneely et al., 2013). Approximately 30% of cows produce inadequate quality colostrum which accounts for 8 to 25% of calf deaths each year (Morrill et al., 2012; Raboisson et al., 2016). Therefore, identification of additional factors contributing to colostrum production in dairy cattle is critical to improve calf survival and health.

Large scale observational studies indicate that environmental factors such as ambient photoperiod, temperature, and humidity may account for differences in colostrum production (Gavin et al., 2018; Cabral et al., 2016). Multiparous Jersey cows calving in a summer month were exposed to temperature-humidity index (THI) values above 80 and produced 6.6 kg of colostrum compared to those calving in a winter month, which only produced 1.3 kg and were exposed to an average THI below 60 (Gavin et al., 2018). Primiparous animals also experienced a drop in colostrum volume from 6.5 kg in summer to 4.2 kg in winter. These decreases in colostrum production during the winter months have been partly attributed to decreases in photoperiod and THI as both have strong correlations with colostrum volume (0.60 to 0.79 ± 0.14 for THI and 0.48 to 0.91 ± for photoperiod) (Gavin et al., 2018). This is further supported in Holstein cows where colostrum yield was positively correlated with the number of days that temperature was above 23°C during the close-up period before calving. However, IgG, a measure of colostrum quality, was negatively correlated with elevated temperature (Cabral et al., 2016). Conversely, Morin et al. (2001) found no differences in colostrum volume or Ig content in Holstein cows after altered photoperiod exposure. Because photoperiod and THI are strongly correlated, previous research controlled the temperature and humidity; therefore, changes in colostrum production were solely attributed to photoperiod.

In addition to impact on colostrum production, 8 h of daylength per day during the dryperiod resulted in increased milk production post-calving by 3.2 to 4.6 kg per day for up to 16 wk of lactation compared to cows exposed to longer photoperiods (Auchtung et al., 2005; Miller et al., 1999; Aharoni et al., 2000; Miller et al., 2000; Lacasse et al., 2014; Crawford et al., 2015).

To date, there is little information on the concordant effects of altered photoperiod and ambient temperature and humidity during the dry period on colostrum production. It is also unknown what management factors during the dry period impact colostrogenesis in dairy cattle breeds. Therefore, the objective of this research was to determine the impact of photoperiod, ambient temperature and humidity exposure during the dry period on subsequent colostrum quantity and quality in Holstein and Jersey cows.

MATERIALS AND METHODS

Animal Management - All animal procedures were approved by the Virginia Polytechnic Institute and State University Animal Care and Use Committee (#17-249 and #18-071). Holstein (n = 137) and Jersey (n = 89) cows were enrolled on a rolling basis from two commercial farms in Virginia from February 2018 through June 2019. Both farms had similar dry off procedures and housed dry cows on pasture. Farm 2 moved cows at 21 days before expected due date to a bedded pack barn where cows were exposed to ambient photoperiod. Farm 1 housed cows on pasture for the entire dry period. The average and range in dry period length for each farm was: Farm 1: 55 ± 1 d (45 to 69 d) and Farm 2: 57 ± 0 d (45 to 70 d) days. Both farms fed separate diets for far-off and close-up cows formulated to meet NRC requirements (Nutrient Requirements of Dairy Cattle, 2021), with cows switching to the close-up ration ~21 days before expected calving date. Both farms fed a far-off ration including corn silage and free-choice grass hay and pasture, while farm 1 close-up cows received corn silage, pelleted feed and free-choice pasture and farm 2 close-up cows received corn silage and pelleted feed and were housed in a bedded-pack barn equipped with fans.

Experiment 1 **-** The specific objective of experiment 1 was to 1) determine the relationship of photoperiod exposure and temperature-humidity index (THI) with colostrum volume and Brix score and 2) determine the impact of breed on the relationship of photoperiod and THI with colostrum production. After parturition, calves were immediately separated from the dam and not allowed to suckle. Calf birth weight was recorded prior to being transported to individual housing. Within 12 hours of calving, colostrum was collected into an individual bucket milker and weighed on a scale, and Brix score was recorded using a Brix refractometer (Vee Gee Scientific, Vernon

Hills) which was calibrated and provided to the farm staff. Farm 1 only housed Jersey cows whereas Farm 2 housed both Holstein and Jersey cows. Given similar management, data from both farms were used for experiment 1. Variables recorded for cows included age of dam, dry off date, length of far off and close up period, inbreeding (F coefficient), sire, calving difficulty, calving date and PTA for milk (kg), fat (kg) and protein (kg). For calves, birth weight and sex were recorded. Data was collected from each farm's animal recording system (PC DART; Dairy Records Management Systems, Raleigh, NC) and the Council on Dairy Cattle Breeding.

Sunrise, sunset, temperature and humidity data were collected for each day that a cow was dry from a local weather station located less than 5 km from each farm (Virtual Weather Crossing). Sunrise and sunset data were used to determine total daily light exposure in minutes. Daily average humidity and maximum daily average temperature were used to calculate average daily THI using the formula (NRC, 1971):

$$\text{THI} = (1.8 \times [\text{MAT}] + 32) - [(0.55 - 0.0055 \times \text{RH}) \times (1.8 \times [\text{MAT}] - 26)]$$

where, MAT is the daily maximum ambient temperature and RH is the daily average relative humidity. Average photoperiod (PHOTO) and maximum THI (mTHI) exposure for the entire dry period, the far-off (FO) period (d -70 to -22 before calving) and the close-up (CU) dry period (d -21 to d 0 of calving) were calculated for analyses. The percent of days during the entire dry period, the FO dry period and the CU dry period that cows were exposed to mTHI greater than 68 was determined.

Experiment 2 – Given the previous evidence that Jersey cows appear to be more sensitive to seasonality, the specific objective of experiment 2 was to determine the relationship of photoperiod and THI on colostrum components in Jersey cows. A 50 mL colostrum sample was collected from Jersey cows into Dairy Herd Information Association (DHIA) collection tubes containing a preservative, put on ice, and shipped to DHIA (Radford, VA) for component analysis (i.e., fat percentage, protein percentage, lactose percentage solids-not-fat (SNF) percentage, somatic cell score (SCS)) via infrared spectroscopy. For farms 1 and 2, all Jersey cows that had colostrum samples collected for DHIA were enrolled in experiment 2. Weather data collected in experiment 1 was also used for experiment 2.

Statistical Analysis –Dry off dates and calving dates were used to determine the length of the dry period. Data were collected from 268 Holstein cows and 278 Jersey cows (Farm 1 Jersey cows n = 152; Farm 2 Jersey cows n = 126), however, only animals having a dry period length of 45 to 70 days long were included in the study. Jersey cows from Farm 1 (n = 43), Holstein cows from Farm 2 (n = 137) and Jersey cows from Farm 2 (n = 46) were included in the final analysis. Cows were subdivided into three class intervals based on CU photoperiod with cow breed distributed as such: PHOTO 1 – CU PHOTO < 708 mins (n = 54 Holstein; n = 22 Jersey), PHOTO 2 – CU PHOTO 709 – 824 mins (n = 43 Holstein; n = 31 Jersey) and PHOTO 3 – CU PHOTO > 825 mins (n = 40 Holstein; n = 36 Jersey). All statistical analyses were completed with SAS 9.4 (SAS; Cary, NC). PROC MEANS was used to determine summary statistics and PROC UNIVARIATE to identify any outliers prior to analysis.

PROC MIXED was used to determine the effect of breed and PHOTO category on colostrum volume, Brix score, fat percentage, protein percentage, SNF percentage, lactose percentage, SCS and calf birth weight. Random effects included animal, farm, dam age at calving (yr), inbreeding percentage, PTA for protein (kg) and CU mTHI.

Residuals of the model were assessed for normality using the AIC and BIC values and transformations were applied as needed. The square root transformation was applied to colostrum volume and Brix score; the log transformation was applied to protein, SNF, lactose and the cube root was applied to fat. Somatic cell score and calf birth weight did not require transformations. Values are reported as the means and standard errors. Significance was determined at $P < 0.05$ and tendencies at $P < 0.80$. Post-hoc power analyses were performed to confirm sufficient power for sample size used.

For regression analyses, a backwards stepwise elimination was used for the GLM procedure to remove non-significant variables until all remaining variables included in the model were significant for each dependent variable. PROC GLM was used to determine the effect of average daily CU and FO PHOTO, average daily CU and FO mTHI exposure and FO and CU percent of days mTHI > 68 on colostrum volume, Brix score and colostrum components. Fixed effects also included farm, breed, dam age at calving (yr), inbreeding percentage, PTA for protein production (kg) and dry period length (d). Transformations were applied to outcome variables as needed to achieve residual normality using the Box Cox procedure of SAS. The fourth root was applied to colostrum volume; Brix score, SNF and protein were squared and the square root was applied to fat. Lactose, somatic cell score, calf birth weight did not require transformations. PROC CORR was used to determine Pearson correlations between variables of interest.

RESULTS

Descriptive Statistics – Descriptive statistics for each breed are displayed in Table 3-1. Holstein and Jersey cows both averaged 4.0 ± 0.1 years of age at calving and averaged 57

± 1 and 56 ± 1 days dry, respectively. Colostrum volume averaged 8.7 ± 0.4 kg for Holstein cows and 5.5 ± 0.4 kg for Jersey cows. Brix score averaged 25 ± 0 % for Holstein cows and 23 ± 0 % for Jersey cows.

***Breed* × *Photoperiod* –** Volume differed by breed × photoperiod category ($P < 0.001$), with Holstein cows producing more colostrum than Jersey cows for each photoperiod category ($P < 0.001$; Figure 3-1). Calf birthweight differed by breed × photoperiod category ($P < 0.001$). Holstein calves were heavier ($P < 0.001$) than Jersey calves for each photoperiod category (Figure 3-3).

Breed – As expected, Holstein cows were predicted to produce more colostrum and had heavier calves compared to Jersey cows ($P < 0.001$; Table 3-3). By photoperiod category, PHOTO 1 cows produced less ($P \leq 0.05$; Figure 3-1) colostrum compared to PHOTO 2 and PHOTO 3 cows within breed.

Photoperiod – For every one unit increase in CU daylength exposure, colostrum volume was expected to increase ($P < 0.001$). This was further supported by a weak but positive correlation with CU PHOTO ($r_P = 0.18$; $P = 0.009$; Table 3-3). Whereas, a one unit increase in average daily photoperiod exposure during the FO period and age of dam was expected to decrease ($P = 0.076$) colostrum volume (Table 3-2). Despite significance in regression modeling, coefficient values were negligible for colostrum volume.

Brix Score differed by farm × PHOTO ($P = 0.021$; Figure 3-2). Specifically, farm 1 cows in PHOTO 3 had the least Brix score compared to PHOTO 1 ($P = 0.009$) and 2 ($P = 0.047$) cows at farm 2. However, within farm, Brix score did not differ by ($P > 0.10$) by PHOTO. There was no predicted relationship between Brix score and photoperiod, but for every one unit increase in age of dam (yr), Brix score was predicted to increase ($P <$

0.001) by 6%. Additionally, farm 1 was predicted to have a decrease (P < 0.001) in Brix score by 12% for cows compared to farm 2 (Table 3-2). Despite no predicted relationship, Brix score was weakly and negatively correlated with FO PHOTO (r_P = -0.17; P = 0.010), CU PHOTO (r_P = -0.22; P = 0.002) and overall PHOTO (r_P = -0.21; P < 0.001)

Colostral protein did not differ (P = 0.709) by PHOTO category (Table 3-4) but was predicted to increase (P = 0.058) by 1.80% for each additional day dry and increase (P = 0.038) by 0.49% for each minute increase in average photoperiod exposure during the far-off dry period. There appeared to be a quadratic effect of colostral lactose with PHOTO category (P = 0.007; Figure 3-4). Specifically, PHOTO 2 lactose decreased by 0.40% and 0.31% compared to PHOTO 1 (P = 0.042) and PHOTO 3 (P = 0.008), respectively. For every yearly increase in dam age, lactose percentage was predicted to decrease (P < 0.001) by 0.52% during the FO period. This was also reflected by a tendency for a weak but negative correlation (r_P = -0.24; P = 0.078) between lactose percentage and FO PHOTO. Additionally, lactose was predicted to increase (P < 0.001) by 0.51% for each minute increase in average daylength exposure during the CU period (Table 3-2). Colostral SCS did not differ (P = 0.317) by PHOTO category (Table 3-4) but was predicted to increases (P < 0.001) by 1.69 for cows calving at farm 1 compared to farm 2 and tended to increase (P = 0.07) by 0.31 for each year increase in dam age (Table 3-2). SCS tended to be weakly, but positively correlated with both FO PHOTO (r_P = 0.26; P = 0.060) and overall PHOTO (r_P = 0.24; P = 0.075).

THI – As expected, there was a strong and positive correlation between overall photoperiod and mTHI (r_P = 0.85; P < 0.001). As the percentage of days int the CU period with mThI > 68 increased, colostrum volume was also predicted to increases ($P < 0.007$). This was further supported by Pearson correlations with weak to moderate positive relationships between colostrum volume with CU mTHI ($r_p = 0.22$; $P = 0.001$) and overall mTHI ($r_p = 0.14$; $P = 0.050$). Conversely, Brix score was weakly and negatively correlated with FO mTHI ($r_p = -0.19$; $P = 0.004$), CU mTHI ($r_p = -0.18$; $P = 0.007$), % CU days of mTHI > 68 ($r_p = -0.18$; $P = 0.007$) and overall % days of mTHI > 68 ($r_p = -0.13$; $P = 0.055$).

Protein was predicted to decrease ($P = 0.014$) by 2.86 for each percentage increase in the number of days of mTHI > 68 during the close-up period (Table 3-2). This was supported by a weak and negative correlation ($r_p = -0.26$; $P = 0.059$) with % CU days of mTHI > 68. Like colostral protein percentage, colostral SNF percentage was predicted to decrease ($P = 0.058$) by 2.49% for each percentage increase in the number of days of mTHI > 68 during the close-up period (Table 3-2). Finally, colostral lactose percentage was weakly and positively correlated ($r_p = 0.29$; $P = 0.030$) with % CU days of mTHI > 68.

DISCUSSION

This study tracks ambient photoperiod and THI exposure in dry Holstein and Jersey cows to determine the effect on subsequent colostrum production post-calving. Average colostrum volume in this study for Holstein (8.7 kg) and Jersey (5.5 kg) cows are slightly greater than the averages reported in literature for Holstein (6.1 to 7.0 kg) and Jersey (4.0 to 4.3 kg) cows, however, values are well within the reported range (Kehoe et al., 2011; Silva-del-Rio et al., 2017; Zarei et al., 2017; Gavin et al., 2018; Soufleri et al., 2021; Valldecabres and Silva-del_Rio, 2021). Increases observed in our study may be attributable to genetic selection pressure on milk production, which would, in turn, increase colostrum production, as early lactation milk production is moderately correlated (r_p = 0.37 to 0.47; $P \leq 0.05$) with colostrum yield (Kessler et al., 2014). Brix score for Holstein (25%) and Jersey (23%) cows were typical based on averages reported in literature for Holstein (24.70% to 27.60%) and Jersey (19.26% to 25.40%) cow Brix scores (Morrill et al., 2015; Borchardt et al., 2022). Based on these values, we determined that both herds are representative of the broader population of Holstein and Jersey cows at farms that are managed similarly. In addition, photoperiod exposure was similar on both farms, with less than an h difference in average daily photoperiod exposure during the close-up period.

Based on previous literature showing that Holstein and Jersey cows produce decreased amounts of colostrum during winter months (Gavin et al., 2018; Borchardt et al., 2022) and that colostrum volume is positively associated with elevated THI and increased light intensity during the prepartum period (Cabral et al., 2016; Westhoff et al., 2023), we expected that colostrum volume would be greatest for cows in the PHOTO 3 category compared to PHOTO 1. This was reflected in both breeds with PHOTO 1 cows producing less colostrum volume than PHOTO 2 and PHOTO 3 cows. Continuous linear regression modeling showed slightly different results, with increased far-off photoperiod predicted to decrease colostrum volume while increased close-up photoperiod was predicted to increase colostrum volume. While the impact of both variables was minimal, the impact of close-up photoperiod exposure was 24,000 × greater than the magnitude of impact of far-off photoperiod exposure. This likely indicates that the close-up period, rather than the far-off period is the critical time point for photoperiod to impact colostrum volume, which coincides with endocrine changes associated with colostrogenesis (Brandon et al., 1971). This datum corroborates Westhoff et al. (2023), who showed that increased average light intensity during the 14 days pre-partum was associated with an increase in colostrum yield. In my study, the far-off period varied in length from 24 to 49 d due to the range in total dry period of 45 to 70 d. Therefore, more variation within the far-off period is present and could mask potential effects of far-off photoperiod on colostrum volume.

Percent of FO dry period days mTHI > 68 predicted a decrease in colostrum volume, which is inconsistent with previous literature that demonstrated increased THI was associated with increased colostrum volume (Gavin et al., 2018; Cabral et al., 2016; Westhoff et al., 2023). However, these three studies were conducted during the 30 days prior to parturition. Therefore, this is the first known study to show an association between THI during only the early dry period and colostrum volume. As previously mentioned, endocrine changes during the 21-day pre-partum period could explain how the observation of decreased light during the far-off period, yet increased light during the close-up period resulted in increased colostrum volume. It is possible that interaction of the environment with the cascade of hormonal events during the close-up period may impact colostrogenesis differently than the far-off period, but with both periods being important to colostrum production.

In addition, it is important to note that cows on this study were exposed to very mild and infrequent heat stress. Only 6.6% of cows had an average close-up mTHI greater than 68 and 62.4% of cows did not have a single day during their dry period where the mTHI was greater than 68. The highest average mTHI for the close-up period was below 72. Heat stress and reductions in performance are not seen at THI values below 68 and generally do not become abundant until a THI of 72 is reached (Bernabucci et al., 2010). Therefore, interpretation and application of these results is most appropriate for cows experiencing mild to no heat-stress. Based on these data, I suggest that colostrum volume increases with increasing photoperiod exposure during the close-up period. Data from cows where average THI for the entire close-up period was above 72 may show slightly different results or a median threshold where colostrum volume is highest between certain THI values.

Incidences of mastitis and pasture forage quality were not available for this study and these factors may have contributed to colostrum quality. Within farm, Brix score was lowest for cows exposed to more daylength and highest for cows exposed to decreased daylength. This suggests an inverse relationship between Brix score and photoperiod. In linear regression modeling, Brix score was not associated with THI or photoperiod exposure but differed by farm. Therefore, it is likely that the difference observed is partially due to differences in management or genetics of the animals between farms. The inverse relationship between Brix score and colostrum volume and Brix score and THI was expected based on previous findings (Westhoff et al., 2023; Zentrich et al., 2019). Westhoff et al. (2023) found that increased average daily light intensity was associated with decreased Brix score (Westhoff et al., 2023). Because colostrum volume and Brix score are inversely related and it is difficult to determine the degree to which these values are impacted by the environment and the degree to which they are impacted by each other. Previous production information for these cows could have assisted in determining the degree to which colostrum volume is impacted by factors other than the environment, however these data were not available. The mechanism by which photoperiod impacts colostrum volume has not been described and research is needed to understand this relationship before associations with Brix score can be described.

Differences in colostrum components for Jersey cows by photoperiod exposure were detected for lactose percentage, but not fat percentage, protein percentage, SNF percentage or SCS. Lactose percentage was increased for PHOTO category 1 and 3. Lactose percentage is associated with increased volume as it draws water into the mammary gland (Fox et al., 2015). Colostrum volume was also increased for PHOTO category 3, but was lowest for PHOTO 1, which does not agree entirely with the lactose findings. In regression modeling, lactose was predicted to increase with increased close-up photoperiod but decrease with increased far-off photoperiod. The confounding photoperiod and lactose relationship remains unexplained, however, there are other significant factors affecting lactose not accounted for in the models, such as the factors previously mentioned. This is reflected by the low (0.27) regression coefficient for the lactose prediction model.

Colostral fat percentage, nor SCS were predicted to be affected by any of the THI or photoperiod variables. However, colostral protein was predicted to increase with increased far-off photoperiod exposure and decrease with increased percentage of days of THI > 68 during the close-up period, with the degree of change being over 5 times greater for the close up period variable. Solids-not-fat percentage was also predicted to be affected by a close-up period parameter, predicting a decrease with increased percentage of days of THI > 68 during the close-up period. This further indicates the importance and increased impact of the close-up period on colostrum rather than the far-off period.

Overall, regression models for the colostrum parameters have weak correlations (r^2 = 0.07 to 0.29) indicating that other factors not accounted for here are impacting colostrum volume and quality. Because variables such as previous protein production were found to be correlated with colostrum parameters in the previous research study, it is likely that inclusion of this data and other parameters would improve the reliability of the models.

CONCLUSION

This study evaluated the impact of both photoperiod and THI during the dry period on both Holstein and Jersey cow colostrum production. Colostrum volume increased with increased photoperiod exposure and was predicted to increase with increased photoperiod exposure, specifically during the close-up period. Brix score decreased with photoperiod exposure, showing an inverse relationship with colostrum volume. Fat percentage followed the same trend as colostrum volume, but only on 1 farm. Lactose and protein were inversely related, being decreased and increased, respectively for the intermediary photoperiod category. Lactose was the only colostrum component that differed by photoperiod category and was highest for both the lowest and highest photoperiod categories. Based on these data, I suggest that while Brix and colostrum volume differ by photoperiod exposure for Holstein and Jersey cows, colostrum components for Jersey cows do not differ by photoperiod exposure. However, protein percentage, SNF percentage and lactose percentage may be affected by both photoperiod and THI according to predictive modeling. The objective of this study, to determine the impact of photoperiod and THI on colostrum in Holstein and Jersey cows confirms previous findings and contributes new findings. Future studies are needed to uncover any potential differences in physiological responses between breeds to THI and photoperiod on a large scale, to manage dry cows for improved colostrum production.

TABLES AND FIGURES

Table 3-1: Descriptive statistics by breed.

	Jersey (n = 89)			**Holstein (n = 137)**		
Item	**Mean ± SE**	**Min**	**Max**	**Mean ± SE**	**Min**	**Max**
Age at Calving (yr)	4.0 ± 0.1	2.6	9.1	4.0 ± 0.1	2.0	9.0
Dry Period Length (d)	56 ± 1	45	70	57 ± 1	45	70
Colostrum (kg)[1]	5.5 ± 0.4	0.7	14.5	8.7 ± 0.4	0.9	20.9
Brix (%)[2]	23 ± 0	11	31	25 ± 0	10	32
Fat (%)[3]	3.54 ± 0.20	0.96	7.05	-	-	-
Protein (%)[3]	14.08 ± 0.40	6.55	18.62	-	-	-
SNF (%)[3]	17.78 ± 0.37	11.07	21.99	-	-	-
Lactose (%)[3]	2.84 ± 0.07	1.63	3.79	-	-	-
SCS[4]	5.14 ± 0.24	1.74	7.74	-	-	-
Calf Wt. (kg)[5]	28.3 ± 1.3	23.1	46.3	41.3 ± 0.6	29.9	49.0
FO Photo (min)[6]	771 ± 11	579	880	730 ± 9	579	882
CU Photo (min)[6]	778 ± 10	579	882	740 ± 9	577	882
Total Photo (min)[6]	773 ± 10	585	876	735 ± 8	582	877
FO mTHI[7]	58 ± 1	46	68	57 ± 1	46	68
CU mTHI[7]	57 ± 1	47	68	58 ± 1	45	69
Total mTHI[7]	57 ± 1	47	67	57 ± 1	48	68
% FO days mTHI > 68[8]	4.3 ± 0.8	0	29.7	4.0 ± 0.7	0	32.7
% CU days mTHI > 68[8]	7.5 ± 1.8	0	66.7	9.6 ± 1.8	0	71.4
% Total days mTHI > 68[8]	7.3 ± 1.3	0	44.1	7.8 ± 1.3	0	47.8

Descriptive statistics were determined using the MEANS procedure of SAS 9.4 (SAS Institute, Inc., Cary, NC)

[1] Colostrum volume determined at first milking post-calving (within one h of calving). Cows were milked completely and colostrum volume was measured on a scale (kg).

[2] Brix score was determined with an optical Brix refractometer at the first milking post-calving (within one h of calving). A composite sample of colostrum was collected aseptically and placed on the Brix face.

[3] Fat (%), protein (%), SNF (%) and lactose (%) were determined by DHIA laboratory via infrared spectroscopy. Composite colostrum samples were collected aseptically at the first milking post-calving (within one h of calving) into 50 mL conical tubes with additive. Samples were frozen within 6 h before being shipped on ice to DHIA.

[4] SCS was determined from a colostrum sample collected aseptically at the first milking post-calving (within one h of calving) and refrigerated within 30 min of collection. SCC was determined using a Cell Counter (DeLaval, Tumba, Sweden). Data were transformed from SCC to SCS using the formula: $SCS = \log_2(SCC/100{,}000) + 3$.

Calf birth weight was determined with a scale by farm staff.

[5] FO, CU and total Photo in minutes corresponds to the average daily photoperiod exposure in minutes that cows were exposed to during the far-off (FO), close-up (CU) or entire dry period (total). Calculated from sunrise and sunset data recovered from a local weather station.

[6] FO, CU and total mTHI corresponds to the average daily maximum THI (mTHI) that cows were exposed to during the far-off (FO), close-up (CU) or entire dry period (total). Calculated from maximum temperature and relative humidity data recovered from a local weather station.

[7] % FO, CU and total days mTHI > 68 corresponds to the percentage of days that cows were exposed to a mTHI greater than 68 during the far-off (FO), close-up (CU) or entire dry period (total). Calculated from maximum temperature and relative humidity data recovered from a local weather station.

Table 3-2: Regression of factors (left column) on dependent variables of interest (top row)

Parameter	Colostrum Volume (kg)	Brix Score (%)	Colostrum Fat (%)	Colostrum Protein (%)	Colostrum SNF (%)	Colostrum Lactose (%)	Colostrum SCS	Calf Birth Weight (kg)
Model r^2 Model *P*-value	0.293 < 0.001	0.102 < 0.001	0.083 0.036	0.169 0.027	0.069 0.058	0.293 < 0.001	0.237 0.001	0.551 < 0.001
Intercept	$2.5e^{-2} \pm 3.6e^{-3}$ (1) 0.106[2]	22 ± 6 < 0.001	3.67 ± 0.20 < 0.001	-12.31 ± 12.37 0.327	14.74 ± 3.45 < 0.001	3.78 ± 2.27 < 0.001	2.73 ± 0.80 0.001	-145 ± 9 < 0.001
PTA Protein (kg)	N/A[3]	N/A	$-1.30e^{-2} \pm 4.53e^{-3}$ 0.036	N/A	N/A	N/A	N/A	N/A
Breed - Holstein	$3.6e^{-3} \pm 1.2e^{-6}$ < 0.001	N/A	N/A	N/A	N/A	N/A	N/A	30 ± 10 < 0.001
Breed - Jersey	0[4]	N/A	N/A	N/A	N/A	N/A	N/A	0
Farm - 1	N/A	-12 ± 5 30.05390 < 0.001	N/A	N/A	N/A	N/A	1.69 ± 0.46 < 0.001	N/A
Farm - 2	N/A	0	N/A	N/A	N/A	N/A	0	N/A
Age at Calving (yr)	$-2.2e^{-3} \pm 2.1e^{-8}$ 0.076	6 ± 3 < 0.001	N/A	N/A	N/A	-1.65 ± 1.01 < 0.001	0.31 ± 0.17 0.072	N/A
Dry Period Length (d)	$3.7e^{-9} \pm 4.6e^{-11}$ 0.003	N/A	N/A	1.80 ± 1.29 0.058	N/A	N/A	N/A	N/A
% FO Days of THI.> 68	$-1.6e^{-9} \pm 3.0e^{-11}$ 0.007	N/A	N/A	N/A	N/A	N/A	N/A	N/A
FO Photoperiod	$-3.3e^{-17} \pm 4.6e^{-15}$ 0.019	N/A	N/A	0.49 ± 0.34 0.038	N/A	-0.52 ± 0.31 < 0.001	N/A	N/A
% CU Days of THI > 68	N/A	N/A	N/A	-2.86 ± 1.79 0.014	-2.49 ± 1.79 0.058	N/A	N/A	N/A
CU Photoperiod	$8.2e^{-12} \pm 1.1e^{-14}$ < 0.001	N/A	N/A	N/A	N/A	0.51 ± 0.32 < 0.001	N/A	N/A

[1] The first value in each row is the parameter estimate ± standard error of the estimate.

[2] The second value in each row is the corresponding *P*-value for the estimate.

[3] N/A indicates that the variable was not significant in the model.

[4] 0 indicates the referent level for which other factors in that variable are compared to.

Table 3-3: Correlation for colostrum parameters and environmental factors with Pearson correlation coefficient value on top and corresponding P-value below.

Variable	**Dry Period Length**[1]	**Volume**[2]	**Brix Score**[3]	**Fat**[4]	**TP**[4]	**SNF**[4]	**Lactose**[4]	**SCS**[4]	**Calf Weight**[5]	**FO PHOTO**[6]	**CU PHOTO**[6]	**FO mTHI**[7]	**CU mTHI**[7]	**% FO Days of THI**[8]	**% CU Days of THI**[8]
Volume	0.04[9] 0.290[10]	———													
Brix Score	0.09 0.160	-0.12 0.076	———												
Fat	-0.05 0.725	**0.33** **<0.01**	0.00 0.964	——											
TP	0.139 0.323	-0.23 0.096	**0.91** **<0.001**	-0.07 0.642	———										
SNF	0.15 0.292	-0.08 0.563	**0.94** **<0.001**	-0.02 0.888	**0.98** **<0.001**	———									
Lactose	-0.09 0.949	**0.358** **0.009**	-0.24 0.080	**0.26** **0.065**	**-0.47** **<0.001**	**-0.31** **0.026**	———								
SCS	**-0.40** **0.003**	-0.01 0.967	-0.12 0.38	0.06 0.694	0.00 0.974	-0.03 0.81	**-0.19** **<0.001**	———							
Calf Weight	**-0.26** **0.034**	**0.322** **0.008**	0.05 0.717	-0.21 0.534	-0.02 0.944	-0.05 0.886	-0.12 0.718	0.48 0.111	———						
FO PHOTO	**-0.11** **0.091**	0.070 0.316	**-0.17** **0.010**	0.143 0.308	0.09 0.51	0.05 0.719	**-0.24** **0.078**	**0.26** **0.060**	-0.18 0.145	———					
CU PHOTO	**-0.15** **0.026**	**0.18** **0.009**	**-0.22** **0.002**	0.19 0.176	-0.04 0.757	-0.06 0.679	-0.06 0.689	0.21 0.121	-0.19 0.118	**0.87** **<0.001**	———				
Overall PHOTO	**-0.14** **0.036**	0.16 0.095	**-0.21** **<0.01**	0.16 0.258	0.04 0.769	0.01 0.949	-0.18 0.202	**0.24** **0.075**	-0.19 0.126	**0.98** **<0.001**	**0.95** **<0.001**				
FO mTHI	-0.07 0.320	0.06 0.404	**-0.19** **0.004**	0.02 0.912	-0.02 0.865	-0.03 0.834	-0.02 0.893	0.10 0.485	-0.09 0.456	**0.85** **<0.001**	**0.71** **<0.001**	———			
CU mTHI	-0.05 0.497	**0.22** **0.001**	**-0.18** **0.007**	0.14 0.328	-0.08 0.562	-0.07 0.642	0.11 0.425	-0.03 0.809	-0.10 0.438	**0.71** **<0.001**	**0.80** **<0.001**	**0.73** **<0.001**	———		
Overall mTHI	-0.07 0.326	**0.14** **0.050**	-0.12 0.085	0.08 0.562	-0.04 0.777	-0.04 0.803	0.04 0.782	0.04 0.771	-0.10 0.427	**0.85** **<0.001**	**0.79** **<0.001**	**0.95** **<0.001**	**0.90** **<0.001**		
% FO Days of THI	0.065 0.341	-0.03 0.678	-0.07 0.305	0.16 0.258	-0.05 0.724	-0.05 0.742	0.04 0.801	0.07 0.607	-0.18 0.148	**0.56** **<0.001**	**0.57** **<0.001**	**0.69** **<0.001**	**0.51** **<0.001**	———	
% CU Days of THI	0.019 0.781	0.08 0.678	**-0.18** **0.007**	0.00 0.989	**-0.26** **0.059**	-0.22 0.109	**0.29** **0.03**	-0.10 0.456	-0.09 0.461	**0.40** **<0.001**	**0.51** **<0.001**	**0.54** **<0.001**	**0.65** **<0.001**	**0.61** **<0.001**	———
% Overall Days of THI	-0.01 0.860	0.02 0.748	**-0.13** **0.055**	0.12 0.377	-0.13 0.354	-0.11 0.438	0.16 0.267	0.012 0.931	-0.16 0.209	**0.55** **<0.001**	**0.61** **<0.001**	**0.70** **<0.001**	**0.65** **<0.001**	**0.90** **<0.001**	**0.88** **<0.001**

Correlations and associated *P*-values were determined using the CORR procedure in SAS 9.4 (SAS Institute, INC., Cary, NC)

[1] Length of the dry period

[2] Colostrum volume determined at first milking post-calving (within one 12 h of calving). Cows were milked completely and colostrum volume was measured on a scale (kg).

[3] Brix score was determined with an optical Brix refractometer at the first milking post-calving (within 12 h of calving). A composite sample of colostrum was collected and placed on the Brix face.

[4] Fat (%), protein (%), SNF (%), lactose (%) and SCS were determined by DHIA laboratory via infrared spectroscopy. Composite colostrum samples were collected at the first milking post-calving (within 12 h of calving) into 50 mL conical tubes with additive. Samples were frozen within 6 h before being shipped on ice to DHIA.

[5] Calf birthweight was recorded on a scale by farm staff within 12 h of calving

[6] FO and CU PHOTO corresponds to the average daily photoperiod exposure in minutes that cows were exposed to during the far-off (FO), close-up (CU) or entire dry period (total). Calculated from sunrise and sunset data recovered from a local weather station.

[7] FO and CU mTHI corresponds to the average daily maximum THI (mTHI) that cows were exposed to during the far-off (FO), close-up (CU) or entire dry period (total). Calculated from maximum temperature and relative humidity data recovered from a local weather station.

[8] FO and CU % days of THI corresponds to the percentage of days that cows were exposed to a mTHI greater than 68 during the far-off (FO), close-up (CU) or entire dry period (total). Calculated from maximum temperature and relative humidity data recovered from a local weather station.

[9] Value depicts correlation coefficient

[10] *P*-value corresponding to correlation coefficient

Table 3-4: Average, standard error and *P*-values by photoperiod category for variables that did not differ by photoperiod category.

	Photoperiod Category			*P*-value
	PHOTO 1	PHOTO 2	PHOTO 3	PHOTO
Colostral Fat[1] (%)	2.90 ± 0.39	4.07 ± 0.38	3.53 ± 0.28	0.159
Colsotral Protein[1] (%)	13.68 ± 0.49	14.89 ± 0.93	13.81 ± 0.56	0.709
Colostral Solids-not-fat[1] (%)	17.53 ± 0.56	18.34 ± 0.87	17.58 ± 0.51	0.787
Colostral SCS[2]	4.17 ± 0.55	5.29 ± 0.46	5.49 ± 0.30	0.317

[1] Colostral fat, protein and solids-not-fat percentage were determined from a colostrum sample collected within 1 h of calving and refrigerated within 30 min of collection. Samples were then frozen in 50 mL collection tubes and shipped to Dairy Herd Information Association (DHIA) for laboratory testing via infrared spectroscopy.

[2] Colostral SCS was determined from a colostrum sample collected within 1 h of calving and refrigerated within 30 min of collection. Samples were then tested for SCC using a Cell Counter (DeLaval, Tumba, Sweden). Data were transformed from SCC to SCS using the formula: $SCS = \log_2(SCC/100{,}000) + 3$

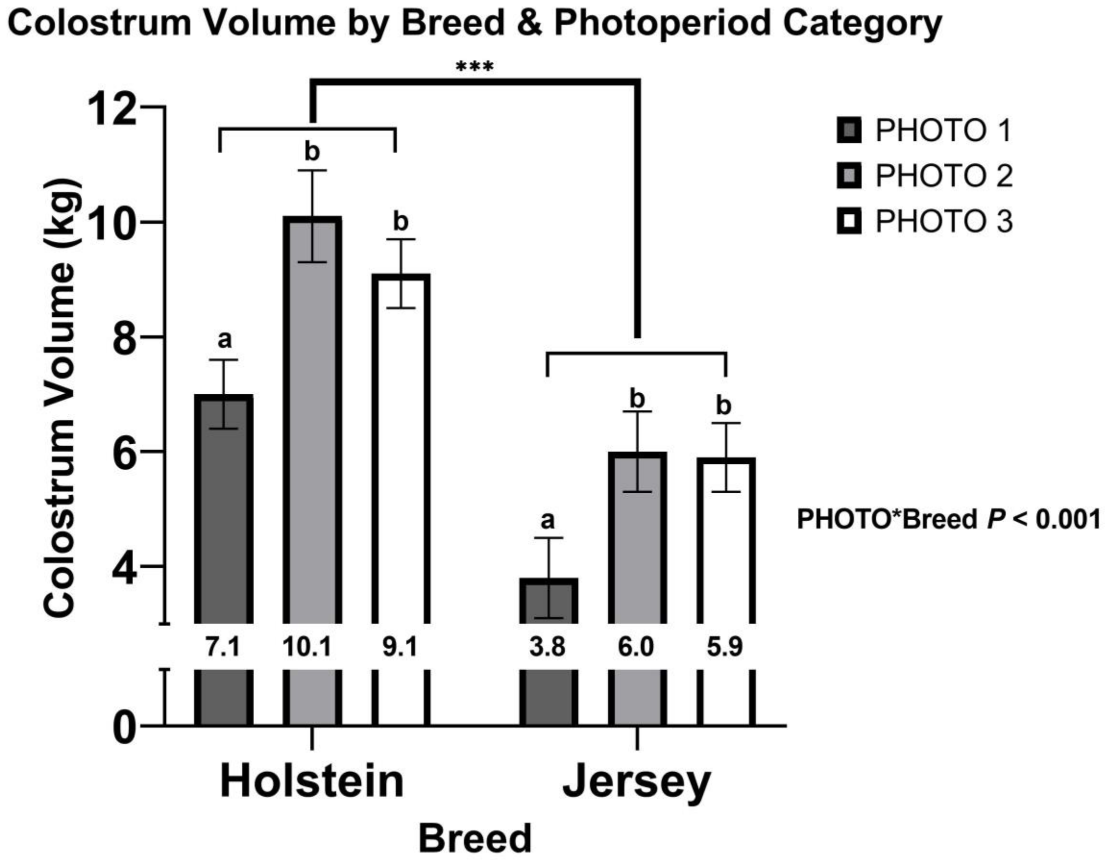

Figure 3-1: Colostrum volume by breed and photoperiod category. Colostrum volume was measured from the first milking within 12 h of calving. Volume differed by photoperiod category × breed ($P < 0.001$), with Holstein cows producing more colostrum than Jersey cows for each photoperiod category ($P < 0.001$). Within breed, PHOTO 1 cows produced less colostrum ($P \leq 0.05$) compared to PHOTO 2 and PHOTO 3 cows for both breeds.

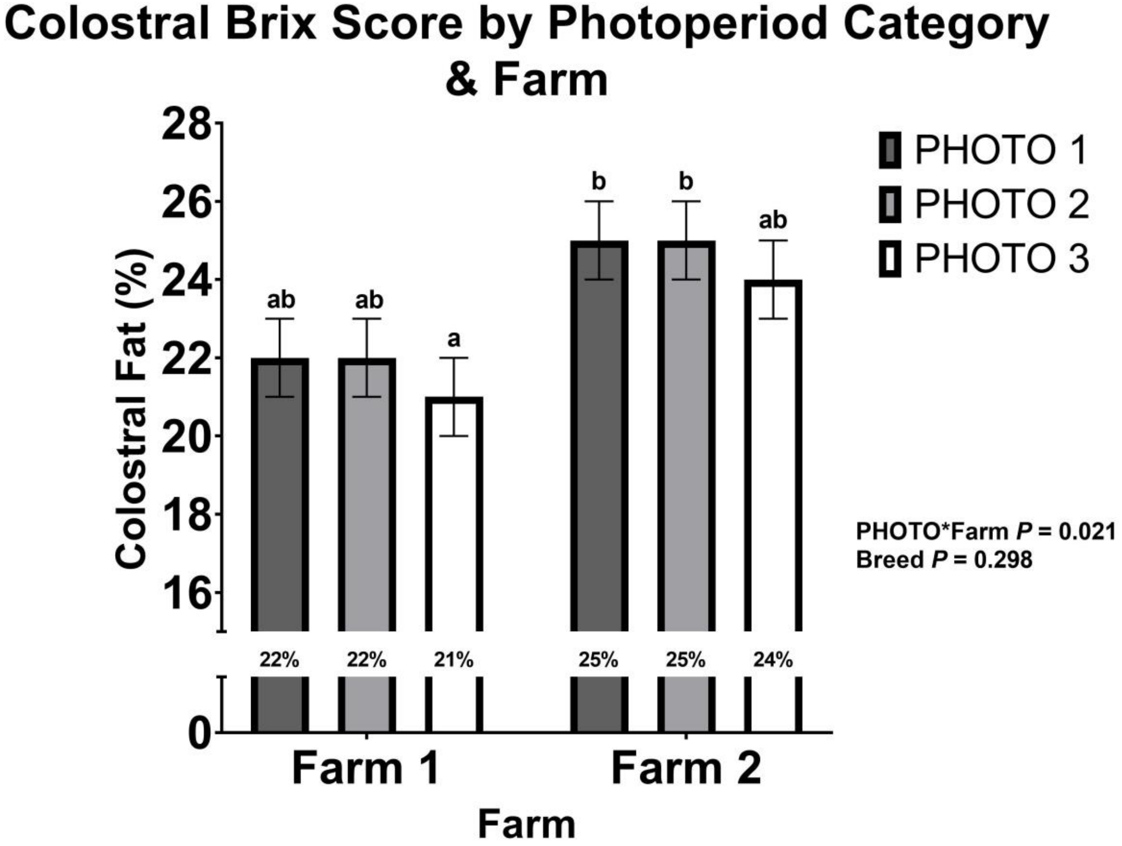

Figure 3-2: Brix score by farm. Brix score did not differ by breed (P =0.298) but differed by photoperiod category × farm (P = 0.021). Farm 1 cows in PHOTO 3 had reduced Brix score compared to PHOTO 1 (P = 0.009) and 2 (P = 0.047) cows at farm 2. Brix score did not differ (P ≥ 0.10) within each farm by PHOTO category.

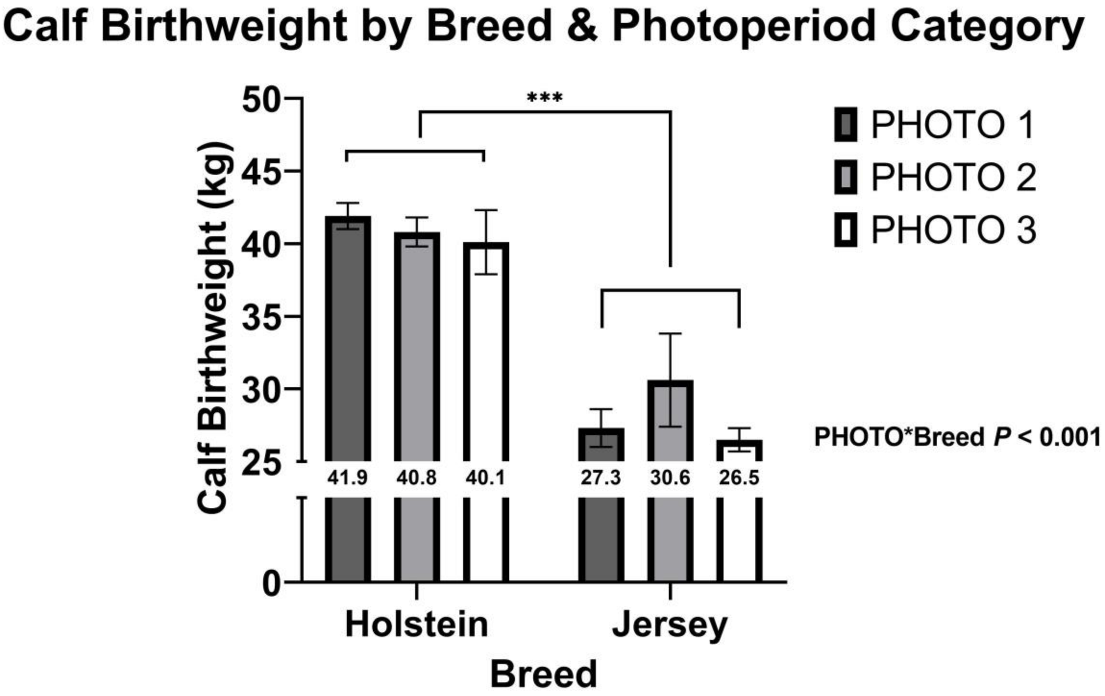

Figure 3-3: Calf birthweight by breed and photoperiod category. Calf birthweight differed by photoperiod category × breed ($P < 0.001$). Holstein calves were heaver ($P < 0.001$) than Jersey calves for each photoperiod category. Within breed, calf birth weight did not differ ($P \geq 0.10$) across photoperiod categories.

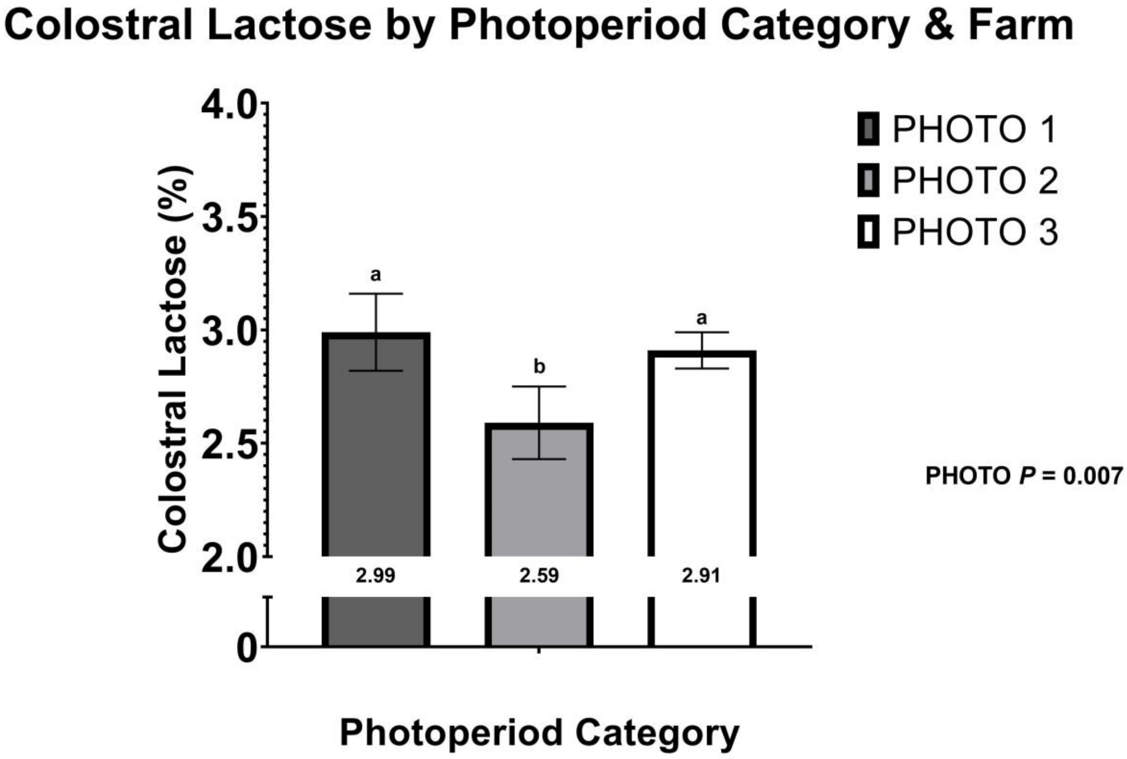

Figure 3-4: Colostral lactose by photoperiod category. Colostral lactose differed by photoperiod category (P = 0.007). PHOTO 2 cows had decreased lactose compared to PHOTO 1 (P = 0.042) or PHOTO 3 (P = 0.008) cows.

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CHAPTER 4: CONCLUSIONS

This study is the first to evaluate the isolated effect of photoperiod during the dry period on colostrum and milk production in Jersey cows and the second to evaluate the effect on colostrum production in Holstein cattle. We found that despite exposure to altered photoperiod when dry, cows would not exhibit differences in milk production after calving if exposed to an inconsistent lighting scheme and we found no effect of photoperiod on colostrum production. This indicates that photoperiod alone is likely not responsible for seasonal variations in colostrum production. Our second study contributes to this theory by showing that seasonal variations in colostrum yield and quality (Brix score) are impacted by both photoperiod and THI exposure.

These findings are important for dairy producers as they indicate that farmers can utilize short-day photoperiod during the dry period during times of moderate THI to improve milk production post-calving (with proper lighting schemes post-calving) without negatively impacting colostrum production. In addition, our findings that Brix score was not highly correlated with colostral Ig content indicate that wide use of Brix score as an indicator of colostrum quality may be responsible for feeding poor quality colostrum to calves and other cost-effective methods to measure colostrum quality should be explored. Results also showed that Jersey cows naturally had higher quality colostrum, evidenced by increased Ig content.

In future studies, I would like to evaluate the effect of controlled photoperiod and controlled THI at various levels to elucidate the impact of the combined effects, when isolated from any other possible environmental factors on colostrum production. In addition, studies to uncover the pathway by which THI and photoperiod impact colostrum production in both Holstein and Jersey cows are needed to improve our understanding of dry cow management and therefore, improve colostrum production. This would include evaluating endocrine changes and differences in mammary cell expression of genes related to milk production. Finally, identification of genetic relationships would allow for genetic selection of cows that produce higher quality colostrum in the future.