Institut für Landtechnik

Colostrum Management on German Dairy Farms

Current State and Potential for Improvements

Dissertation

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Abstract

Calf rearing is the fundament of any dairy farm. In consequence, colostrum management is an important part of calf rearing because calves are passively immunized through colostrum uptake. Therefore, colostrum management is of particular importance for healthy calves and long-lasting performances of cows and should be optimized. However, high mortality and morbidity rates of 3.0–15.0% in German calf rearing indicate that colostrum management has enormous potential for improvement. The objective of this thesis was to identify potential strategies for enhancement and to underscore the significance of optimized colostrum management on German dairy farms. The thesis offers a comprehensive account of colostrum management and its implications for calf development.

Study 1 looked at indirect and direct methods of measuring colostrum quality. Direct methods are not easily applicable in practice, so farmers have to resort to indirect methods such as colostrometers and refractometers. Indirect methods allow conclusions about the concentration of Ig in colostrum, which can be used to assess the quality of the colostrum. In addition, the parameters influencing the Ig concentration were investigated in Study 1. Many parameters can be considered and positively influenced by the farmer. In particular, yield, parity and temporal aspects serve as key factors. Newer aspects such as dry period, seasonal influences and genetics are becoming increasingly important, but their impact on Ig concentrations has not been sufficiently investigated. Furthermore, there is a particular need for research in the area of data management.

To gain an overview of colostrum management practices on German dairy farms, a 33-question online survey focusing on frozen colostrum storage was developed (Study 2). The survey highlighted areas where a more targeted knowledge transfer can improve colostrum management. In addition, there appeared to be a lack of “Standard Operating Procedures” for employees on the practical implementation of colostrum management. Particular attention should be paid to the regular determination and documentation of Ig concentrations. The added value of stored colostrum should also be emphasized, especially for smaller farms.

Based on the two studies, the three areas of work organization, knowledge transfer, and data management were placed in the context of improved colostrum management. The objective was to identify the most important future tasks and implementation challenges to achieve adequate colostrum management of German dairy farms.

Kurzfassung

Die Kälberaufzucht ist die Basis eines jeden Milchviehbetriebes. Insbesondere das Kolostrummanagement ist ein wichtiger Bestandteil der Erstversorgung, da die Kälber über das Kolostrum eine passive Immunisierung erfahren. Hohe Mortalitäts- und Morbiditätsraten in der deutschen Kälberaufzucht von 3.0–15.0 % zeigen jedoch, dass das Kolostrummanagement ein enormes Optimierungspotenzial aufweist. Ziel dieser Dissertation war es, Verbesserungsstrategien aufzuzeigen und die Bedeutung eines optimierten Kolostrummanagements in deutschen Milchviehbetrieben hervorzuheben. Die Arbeit bietet eine umfassende Darstellung des Kolostrummanagements und seiner Auswirkungen auf die Kälberentwicklung.

Studie 1 beschäftigte sich mit indirekten und direkten Messmethoden zur Erfassung der Kolostrumqualität. Direkte Messmethoden sind in der Praxis nicht ohne weiteres anwendbar, daher müssen die Landwirte meist auf indirekte Methoden mittels Kolostrometer oder Refraktometer zurückgreifen. Indirekte Methoden lassen Rückschlüsse auf die Ig-Konzentration im Kolostrum zu, wodurch die Qualität des Kolostrums beurteilt werden kann. Weiterhin wurden in Studie 1 die Einflussfaktoren auf die Ig-Konzentration untersucht. Es gab zahlreiche Einflussfaktoren, die jedoch vom Landwirt berücksichtigt und positiv beeinflusst werden können. Insbesondere die Kolostrummenge, Laktation und zeitliche Aspekte spielen eine wesentliche Rolle. Neuere Aspekte wie Trockenstehzeit, saisonale Einflüsse und Genetik gewinnen an Bedeutung, ihr Einfluss auf die Ig-Konzentration ist aber noch nicht ausreichend untersucht. Außerdem besteht vor allem im Bereich des Datenmanagements Entwicklungsbedarf.

Um einen Überblick über die Praxis des Kolostrummanagements in deutschen Milchviehbetrieben zu erhalten, wurde eine Online-Umfrage mit 33 Fragen entwickelt (Studie 2), die sich auf gefrorene Kolostrumreserven konzentrierte. Die Umfrage zeigte Bereiche auf, in denen ein gezielterer Wissenstransfer das Kolostrummanagement verbessern kann. Darüber hinaus schien es an konkreten, umsetzbaren Anweisungen (sog. Standard Operating Procedures) für das Personal zur praktischen Umsetzung des Kolostrummanagements zu mangeln. Dabei sollte vor allem auf die regelmäßige Bestimmung und Dokumentation der Ig-Konzentrationen Wert gelegt werden. Auch der Mehrwert von gelagertem Kolostrum im Vergleich zu einem höheren Arbeitsaufwand sollte insbesondere in kleineren Betrieben hervorgehoben werden.

Auf Basis der beiden Studien werden die drei Bereiche Arbeitsorganisation, Wissenstransfer und Datenmanagement in den Kontext eines verbesserten Kolostrummanagements gestellt. Um das Kolostrummanagement in deutschen Milchviehbetrieben zu verbessern, war es das Ziel, die wichtigsten zukünftigen Aufgaben und Herausforderungen bei der Umsetzung zu identifizieren.

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List of Abbreviations

AHDB	Agriculture and Horticulture Development Board
AMS	Automated milking system
BLE	Bundesanstalt für Landwirtschaft und Ernährung / Federal Office for Agriculture and Food
BMEL	Bundesministerium für Ernährung und Landwirtschaft / Federal Ministry of Food and Agriculture
BMJ	Bundesministerium der Justiz / Federal Ministry of Justice
cfu	Colony forming unit
CI	Confidence interval
EC	European Commission
ELISA	Enzyme-linked immunosorbent assay
EU	European Union
FCR	Frozen colostrum reserves
FIR	Far-infrared spectroscopy
FPT	Failure of passive transfer
Ig	Immunoglobulin
IgA	Immunoglobulin A
IgE	Immunoglobulin E
IgG	Immunoglobulin G
IgM	Immunoglobulin M
IR	Infrared spectroscopy
IU	International unit
L	Lactation
MIR	Mid-infrared spectroscopy
na	Not available
n. d.	No data
NIR	Near-infrared spectroscopy
NOR	No reserves
p.p.	Postpartum

PraeRi	Tiergesundheit, Hygiene und Biosicherheit in deutschen Milchkuhbetrieben – eine Prävalenzstudie
Q1	First quartile
Q3	Third quartile
RID	Radial immunodiffusion
SCC	Somatic cell count
SD	Standard deviation
Se	Sensitivity
SOP	Standard operating procedure
Sp	Specificity
STIGA	Split trehalase IgG quantification assay
STP	Serum total protein
Task_Doc	Office work and documentation
Task_Feedcalf	Feeding of calves
Task_Feedcow	Feeding of cows
Task_Lead	Operations, management, and investment
Task_Milk	Milking Cows
Task_Stable	Stable work
Task_Tech	Machine guidance and technical maintenance
Task_Treatcalf	Treatment of calves
Task_Treatcow	Treatment of cows
TCC	Total coliform count
TIA	Turbidimetric immunoassay
TierSchuNutztV	Tierschutz-Nutztierhaltungsverordnung / Order on the protection of animals and the keeping of production animals
TIR	Transmission infrared spectroscopy
TPC	Total plate count
TPI	Transfer of passive immunity
TreA	Enzyme trehalase
USDA	United States Department of Agriculture
ZST	Zinc sulfate turbidimetry

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1 Introduction

1.1 General Introduction

Ensuring the welfare and optimal development of calves is a critical issue on dairy farms. Therefore, calf rearing faces major challenges in these areas. Calves play a crucial role in herd remounting, but their health can be compromised by diseases, resulting in increased treatment, losses, and economic costs (Zitzmann et al., 2019; Carulla et al., 2023). Calf rearing is a key factor that considerably influences the subsequent production and reproductive performance of cows (Smith, 2012; Aghakeshmiri et al., 2017; Carulla et al., 2023), including growth rate, health, longevity, and milk production (Wathes et al., 2008; van de Stroet et al., 2016). Additionally, changing consumer attitudes have created a growing demand for systems adapted to the specific needs of each species or animal. The welfare and health of calves associated with different rearing systems have become more relevant in recent years (Frewer et al., 2005; Halachmi et al., 2019).

Effective colostrum management is a key factor in the optimal physiological and immunological development of calves. The supply of colostrum provides important biological and health functions, particularly in the immune system. Numerous studies have demonstrated the significance of colostrum intake for calf welfare (Hammon et al., 2020; Carulla et al., 2023). Calves receiving sufficient colostrum have increased growth, improved immune system function, metabolic development, and higher blood concentrations of immunoglobulin G (IgG) (Schäff et al., 2014; Lago et al., 2018; Quigley et al., 2019). Colostrum intake is necessary for the passive immunization of calves, as they are born with an underdeveloped immune system (Becker and Märtlbauer, 2016). An adequate supply of immunoglobulins (Ig) through colostrum also reduces the incidence of respiratory disease (Lora et al., 2018b). In addition, lower concentrations of serum IgG and total serum protein in the first three days postpartum (p.p.) are associated with reduced growth (Furman-Fratczak et al., 2011; Cuttance et al., 2018). Various methods are available to measure colostrum quality early and to verify sufficient blood Ig concentrations. Low blood concentrations may also indicate management errors (Godden et al., 2019; Souza et al., 2021).

However, problems in colostrum management have been identified in German calf rearing due to the persistence of high morbidity and mortality rates (PraeRi, 2020). Therefore, changes to reduce these rates are necessary. As explained, colostrum management offers an opportunity to intervene positively in the management process at an early stage, resulting in positive lifelong consequences for animal welfare and development.

1.2 Structure and Objectives of the Thesis

The objective of this thesis is to identify areas for improvement and to emphasize the significance of enhancing colostrum management on German dairy farms. It provides a comprehensive account of managing colostrum and its impact on the calf's development.

Section 1 introduces the broad topic of the thesis, outlining its scope and structure. Section 2, the literature overview, examines the role of colostrum in animal health. Following this, Section 2.1 explains the process of passive immunization and its essential role for calves. It also provides information on the background of Ig absorption, which is directly related to passive immunization, and the factors that influence absorption. The section describes the consequences of insufficient resorption, which can lead to failure of passive transfer of immunity, and how these consequences relate to successful calf rearing. Section 2.2 outlines the 5 Q`s of colostrum management, which serve as a starting point for actively improving colostrum management. Section 2.3 combines this information with details of calf rearing in Germany. It briefly describes conventional calf rearing on typical German dairy farms and why better colostrum management is needed. Section 2.4 describes factors that can improve colostrum management, e.g., “Standard Operating Procedures” (SOPs), knowledge transfer, and data management. The relevant sources are listed in Section 2.5.

Section 3 provides the published review article and Section 4 presents the published research article. Study 1 covers information on direct and indirect methods of measuring Ig concentration in colostrum. Additionally, it summarizes factors related to Ig concentration (e.g., animal-related and environmental factors) and provides recommendations for farmers for better colostrum management. Study 2 (Section 4) focuses on the current state of colostrum management on German dairy farms. The study is based on an online survey distributed through various channels to German dairy farmers. The survey included 33-questions about standard colostrum management practices, such as measuring Ig concentration, as well as the management of frozen colostrum reserves. The purpose of the survey was to assess the current knowledge and handling of German farmers regarding colostrum management. Based on this, knowledge gaps and the need for targeted knowledge transfer in specific areas were defined.

Section 5 discusses three aspects – SOPs (Section 5.1), knowledge transfer (Section 5.2), and data management (Section 5.3) – in the context of colostrum management. The analysis is based on the findings presented in Sections 2, 3, and 4. The objective of Section 5 is to determine how these three characteristics can enhance colostrum management on German dairy farms.

The dissertation closes with a conclusion of the main findings (Section 5.4).

2 Literature Overview

2.1 Colostrum and Calf Health

Milk is a liquid produced by female mammals in the mammary gland to provide newborns with necessary nutrients and support physiological functions (McGrath et al., 2016). Dairy milk is composed of approximately 12.0% dry matter and 88.0% water (Becker and Märtlbauer, 2016). Colostrum is the secretion produced in the mammary gland during or prior to the parturition of cows. Furthermore, it is a natural source of macro- and micronutrients, Igs, proteins, and growth factors for the calf (Playford and Weiser, 2021). The transfer of Igs from the maternal circulation to the mammary gland is known as colostrogenesis, which utilizes the same hormones as lactogenesis. While lactogenesis initiates milk synthesis and secretion, colostrogenesis refers to the process of milk synthesis during the immediate parturition period. Several weeks prior to calving, the hormones prolactin, estrogen, and progesterone stimulate colostrogenesis. This process is regulated both by endocrine control mechanisms and local molecular regulation (Barrington et al., 2001; Godden et al., 2019).

Pre-colostrum is the first milk produced by the mammary gland. Lactose in pre-colostrum is the first indicator that the alveolar epithelial cells have fully differentiated for milk secretion, which occurs ten days before birth. It contains large molecules such as Igs, fat globules, proteins, epithelial cells, leukocytes, and ions (Becker and Märtlbauer, 2016). Colostrum, otherwise, is produced and secreted two to seven days before birth and two to three days after birth. Colostrum is a thick, yellowish substance with a slightly acidic pH of 6.4 (Becker and Märtlbauer, 2016; Puppel et al., 2019). The composition of mature milk and colostrum differs greatly due to their different nutritional meanings (Barrington et al., 2001; Playford and Weiser, 2021). Changes in the milk composition can provide insights into the animal's health status (Becker and Märtlbauer, 2016).

2.1.1 Passive Immunization and Resorption of Immunoglobulins

In addition to numerous essential ingredients, the colostrum provides the calf with passive immunity. Newborn calves' immune systems are unable to fight infectious pathogens within the first few weeks after birth due to the physical nature of the cow´s placenta, which prevents the transfer of macromolecules, i.e., Igs, to the calf (Becker and Märtlbauer, 2016). Therefore, calves depend on an early and abundant supply of colostrum to absorb antibodies orally to protect themselves from infections. This method is known as passive immunization, as it relies on the mother's antibodies (Becker and Märtlbauer, 2016). Igs can be absorbed from colostrum through the calf's intestine within its first 24 to 36 h of life. However, the transfer rate continuously declines

(Broughton and Lecce, 1970). The newborn calf's physiological characteristics facilitate this absorption. Firstly, the intestinal barrier of the newborn calf is still permeable to macromolecules. Secondly, the proteolytic activity in the calf's intestine is not yet strongly developed. Additionally, colostrum contains trypsin inhibitors that prevent protein cleavage in the intestine. The peak uptake of Ig in the intestine occurs within the first 6 h of life and decreases continuously thereafter. This time restriction is due to the development of the calf's enterocytes and digestive system. After 24 h, the enterocytes can no longer absorb the Igs intact (Staley et al., 1972; Weaver et al., 2000). On the second day p.p. the intestinal barrier closes due to tight junctions, which prevents further absorption of Ig (Figure 2.1). Moreover, the composition of colostrum changes rapidly within hours after birth (Table 2.1), resulting in a decrease in its biological and promotional effects over time (Puppel et al., 2019).

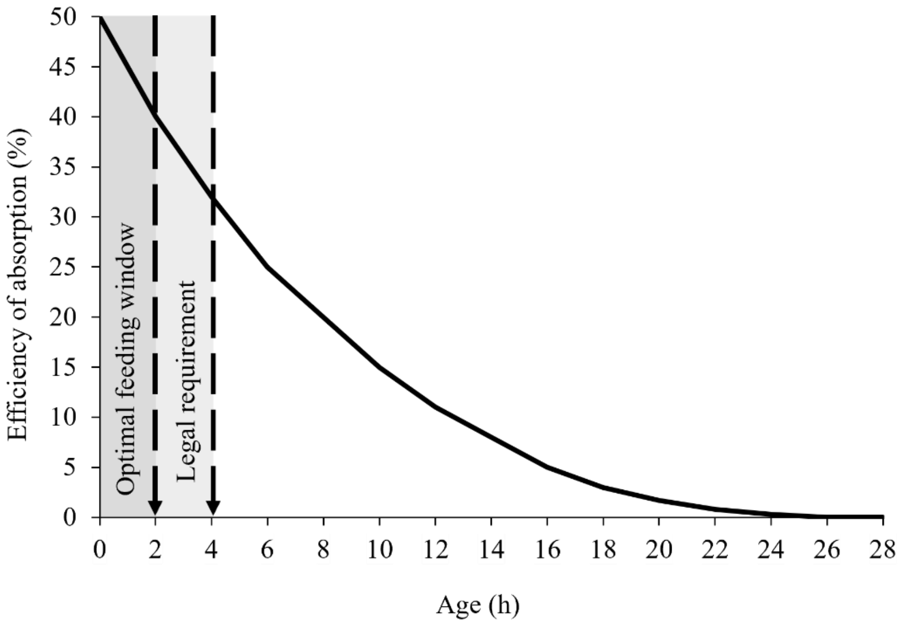

Figure 2.1 Changes in apparent efficiency of IgG absorption (%) with increasing age (h) in newborn calves, including the optimal feeding window and the legal requirement for colostrum feeding in Germany (adapted after AHDB, 2023).

Passive immunization has an immediate effect but is not long-lasting. Unlike active immunization, passive immunization involves the breakdown of antibodies within a specific time frame (Hedegaard and Heegaard, 2016). The calf´s plasma IgG levels remain stable for several weeks, protecting against infections until the calf can produce Ig independently. While still protected by maternal antibodies (passive immunity), the calf's immune system begins producing its own antibodies (active immunity). The period when the calf transitions from passive to active immunity is known as the “immunological gap” (Figure 2.2). During this time, the calf is more susceptible to infectious diseases. This susceptibility typically occurs between the second and seventh week of life, as the calf's immune system matures after birth. The older the calf, the more capable its immune system becomes. Calves usually develop sufficient active immunity to resist infections by the 12th week of life (Chase et al., 2008; Hulbert and Moisá, 2016; Lopez et al., 2020).

Table 2.1 Chemical compositions of colostrum and milk (%) at particular hours after calving, adapted by Horecka (2016), Puppel et al. (2019) and Godden et al. (2019).

Time after Calving (h)	**Total Solids** (%)	**Protein** **Total** (%)	**Casein** (%)	**Albumin, Globulin** (%)	**Fat** (%)	**Lactose** (%)
0	23.9	16.8	4.1	12.7	6.7	2.9
6		11.7	3.5	8.0	6.1	3.5
12	17.9*	6.3	3.1	3.2	4.4	3.9
24		5.5	2.9	2.6	4.1	4.1
48	14.1*	4.8	2.8	2.0	3.9	4.2
120		3.6	2.7	0.9	0.8	4.5
Milk	12.9	3.2	2.6	0.6	3.8	4.6

*It was not possible to allocate total solids on an hourly basis. The source (Godden et al., 2019) only provides an allocation for each milking p.p. (2nd milking =17.9%, 3rd milking = 14.1%).

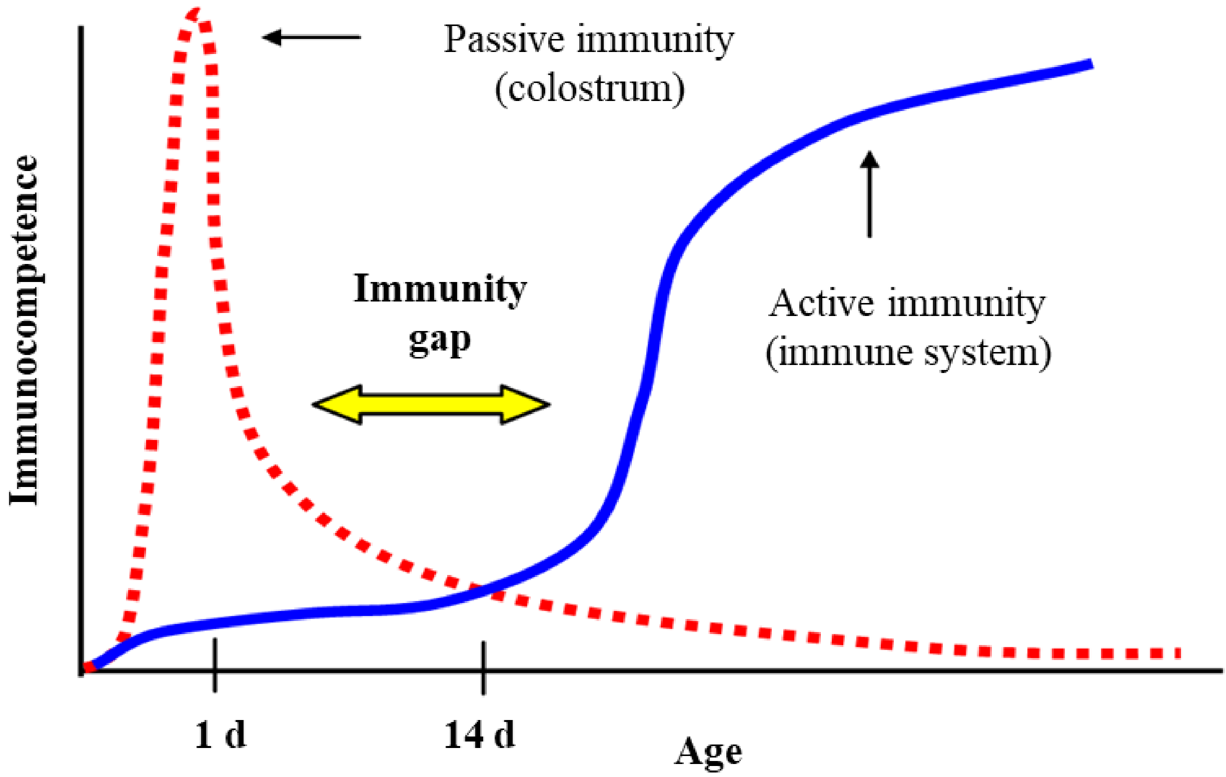

Figure 2.2 Development of passive and active immunity in the calf (adapted after Jones and Heinrichs, 2022).

2.1.2 Failure of Passive Transfer of Immunity

Numerous studies have investigated the transfer of passive immunity (TPI), but failed transfer of passive immunity (FPT) remains a frequent occurrence in calf rearing, negatively affecting animal welfare and economic aspects (Atkinson et al., 2017). FPT is defined as a serum IgG concentration < 10.0 mg mL^{-1} when measured 24 and 48 h p.p. or as a concentration of serum total protein (STP) < 5.2 g dL^{-1} (Godden et al., 2019; Lombard et al., 2020). In contrast, a serum IgG concentration > 15.0 mg mL^{-1} is considered an excellent TPI (Shivley et al., 2018). Table 2.2 displays serum IgG and STP concentrations from various studies. Serum IgG concentrations range from 13.3–25.5 mg mL^{-1}, while STP concentrations range from 5.2–6.0 g dL^{-1}. Refractometer readings determined values between 8.5% and 10.5% Brix. Despite the well-known importance of colostrum management, the prevalence of FPT remains high worldwide (Trotz-Williams et al., 2008; Vogels et al., 2013; Lora et al., 2018a). Table 2.3 displays the greatly varying values of FPT prevalence across different studies. Most studies report a prevalence of > 20.0%, while only a very small percentage report a prevalence of ≤ 10.0%.

Numerous studies have established limit values for TPI (Lombard et al., 2020; Sedó et al., 2023). However, Sedó et al. (2023) argued that the straightforward division of FPT into < 10.0 mg IgG mL^{-1} and > 10.0 mg IgG mL^{-1} underestimates the importance of passive transfer. This is because the effects of different serum IgG concentrations are not adequately represented. Barry et al. (2019) suggested to reconsider the cut-off point of 10.0 mg mL^{-1}, as they found no difference in calf mortality rates. However, Robison et al. (1988) recorded a twofold increase in mortality in calves with serum IgG concentrations < 12.0 mg mL^{-1}. In 2020, Lombard et al. defined four categories for serum IgG concentration: poor < 10.0 mg mL^{-1}, fair = 10.0–17.9 mg mL^{-1}, good = 18.0–24.9 mg mL^{-1}, and excellent ≥ 25.0 mg mL^{-1}. These categories are adopted by Sedó et al. (2023) and served as a rationale, that, based on the available scientific evidence, a higher serum IgG concentration should be targeted to reduce calf mortality rather than relying on the traditional binary values to determine FPT.

Table 2.2 Serum IgG concentrations, STP concentrations, and serum IgG concentrations quantified by refractometer in calves after feeding with colostrum in different studies.

Reference	**n**	**Serum IgG concentration** (mg mL^{-1})		**STP concentration** (g dL^{-1})		**Serum IgG concentration, Brix Refractometer** (%Brix)	
		Mean ± SD	Min. - Max.	Mean ± SD	Min. - Max.	Mean ± SD	Min. - Max.
Vandeputte et al. (2011)	108	23.1 ± 7.5	(7.3–45.3)				
Alley et al. (2012)	100	15.2 ± 0.71	(4.6–36.4)				
Morrill et al. (2013)	185	19.0 ± 9.7	(3.5–47.0)			8.6 ± 0.9	(6.8–11.0)
Chigerwe and Hagey (2014)	46	18.5 ± 8.6	na			10.2 ± 1.7	na
Deelen et al. (2014)	397	24.1 ± 10.0	(2.1–59.1)	6.0 ± 0.8	(4.4–8.8)	9.2 ± 0.9	(7.3–12.4)
Thornhill et al. (2015)	48	25.5 ± 19.1	(1.2–39.0)			10.5 ± 2.9 10.5 ± 2.5	(7.2–12.5) (7.1–12.0)
Elsohaby et al. (2015)	203	17.7 ± 10.4	(1.3–60.0)	6.0 ± 1.0*	(4.2–10.6)	8.8 ± 1.0	(5.9–12.9)
Hernandez et al. (2016)	310	21.3 ± na	(8.1–41.2)	5.8 ± na 5.0 ± na	(3.9–7.8)[a] (3.5–7.2)[a]	9.2 ± na 8.5 ± na	(7.0–11.5)[a] (6.6–11.0)[a]
Hernandez et al. (2016)	112	38.0 ± 6.6	(23.4–53.1)	6.8 ± 0.5	(5.4–8.0)	10.2 ± 0.7	(8.3–11.8)
McCracken et al. (2017)	97	23.7 ± 12.5	(2.3–65.5)	5.8 ± 1.0	(3.7–8.4)	8.9 ± 1.1	(6.5–12.0)
Zakian et al. (2018)	160	16.5 ± na	(11.2–20.0)			8.5 ± na	(8.1–9.2)
Renaud et al. (2018)	149	19.9 ± 10.6	(1.1–57.3)	5.6 ± 0.7	(4.1–7.9)	na	na
Barry et al. (2019)	na	30.9 ± 13.4	na				
da Costa Corrêa Oliveira et al. (2019)	227	18.4 ± 11.6	(1.1–55.5)	5.9 ± 0.7	(4.4–8.0)	9.0 ± 0.85 9.0 ± 0.87	(6.9–11.6) (7.2–11.6)
Elsohaby et al. (2019)	217	13.3 ± 9.3	(1.6–51.4)	5.2 ± 0.8	(3.6–8.6)	8.6 ± 0.9 8.8 ± 1.0	(6.8–12.3) (6.3–12.2)
Sutter et al. (2020)	216	17.1 ± 9.8	(0.8–47.8)	5.3 ± 0.6*	(4.0–7.4)	8.2 ± 0.78	(6.6–11.1)

*Measured by refractometer; [a]two different populations of Holstein calves; IgG = Immunoglobulin G; Max. = Maximum; Min. = Minimum; na = Not available; SD = Standard deviation; STP = Serum total protein;

Table 2.3 Proportion of calves with serum IgG concentration < 10.0 mg mL^{-1} and ≥ 10.0 mg mL^{-1} and the proportion of FPT in different studies.

Reference	Country	n	< 10.0 (mg mL^{-1})	≥ 10.0 (mg mL^{-1})	Prevalence FPT (%)
Dawes et al. (2002)	USA	119	14	105	11.8
Calloway et al. (2002)	USA	90	45	45	50.0
Beam et al. (2009)	USA	2,030	391	1,639	19.2
Alley et al. (2012)	USA	100	24	76	24.0
Morrill et al. (2013)	USA	200	50	150	25.0
Deelen et al. (2014)	Canada	397	19*	378*	4.8
Chigerwe and Hagey (2014)	USA	46	8	38	17.4
Thornhill et al. (2015)	Australia	48	11	37	23.0
Elsohaby et al. (2015)	Canada	203	55	148	27.5
Atkinson et al. (2017)	Canada	380	61*	319*	16.0
McCracken et al. (2017)	USA	97	9	88	10.0
Renaud et al. (2018)	Canada	149	31	118	21.0
Zakian et al. (2018)	Iran	160	20	140	13.0
da Costa Corrêa Oliveira et al. (2019)	Germany	227	67	160	30.0
Elsohaby et al. (2019)	Canada	217	94	123	43.3
Sutter et al. (2020)	Germany	216	59	157	27.0

*Calculated independently on the basis of the given values; FPT = Failure of transfer of passive immunity

Management measures that affected FPT, included providing low-temperature heat sources for calves, born through difficult births and veterinary care for calves born in incorrect body positions (Beam et al., 2009). The research conducted by Olson et al. (1980) found that cold stress can negatively impact the rate of Ig uptake by the calf. The calf´s breed may also influence the mortality risk. For calves of beef breeds, a lower serum IgG concentration (< 8.0 mg mL^{-1}) was associated with an increased risk of mortality compared to those with a higher concentration (> 16.0 mg mL^{-1}). In Holstein calves, mortality was twice as high when serum IgG concentrations were < 12.0 mg mL^{-1} (Robison et al., 1988).

2.2 The 5 Q's of Colostrum Management

The importance of colostrum for newborns is undeniable. However, cow- and management-related factors can have a negative impact on colostrum and its composition. In order to generate the best outcome from colostrum, five criteria, also known as the 5 Q's of colostrum management, are often used: Quality, Quantity, Quickness, Quite Clean, and Quantification. These factors influence each other, making it difficult to distinguish between them. The following sections will provide detailed explanations of the 5 Q's of colostrum management.

2.2.1 Quality

Although colostrum contains many important factors for calf development, the concentration of Igs has traditionally been used to determine colostrum quality. The term high-quality or "good" colostrum is often mentioned without a precise definition. In the context of this dissertation high-quality refers to colostrum that contains ≥ 50.0 mg IgG mL^{-1}. However, IgG concentrations can be influenced by many factors and can vary significantly between herds and individuals (Godden et al., 2019; Geiger, 2020). The concentration of Ig in the colostrum affects the amount of IgG absorbed (Quigley et al., 2013), which can lead to FPT. The risk of FPT decreases by 3.0% ($P < 0.001$) for each additional gram of Ig per liter (Lora et al., 2018a). This finding is supported by the work of Shivley et al. (2018), who found that for every 10.0 mg mL^{-1} increase in colostrum IgG concentration, there was a 1.1 mg mL^{-1} increase in serum IgG. Barry et al. (2019) found no significant difference in the probability of mortality for calves with serum IgG concentrations < 10.0 mg mL^{-1} or > 10.0 mg mL^{-1}. However, numerically the risk was twice as high at concentrations < 10.0 mg mL^{-1}. Higher quality colostrum leads to better TPI, provided that it can be absorbed in sufficient quantities and in a timely manner. Raboisson et al. (2016) estimated that the cost of FPT per dairy calf is approximately 60 €, with a range of 10–109 €. The best-case scenario costs 52 €, while the worst-case scenario costs 285 €. FPT has been linked to higher mortality rates in several studies (Urie et al., 2018; Lombard et al., 2020). Multiple studies have shown that high serum IgG concentration provides postnatal benefits (Furman-Fratczak et al., 2011; Sutter et al., 2023; Aghakhani et al., 2023). Thus, serum IgG concentration is a reliable indicator of calf morbidity and mortality, and is a significant benchmark for assessing colostrum management quality (Lombard et al., 2020; Geiger, 2020). However, despite its impact on animal welfare and economics, few farms measure calves' passive transfer status (Vasseur et al., 2010). The United States Department of Agriculture (USDA) conducted a study in 2016 in the United States, which found that only 6.0% of farms monitor blood levels for FPT (USDA, 2016). Furthermore, Beam et al. (2009) discovered that STP concentrations were recorded on only 3.3% of the surveyed farms. They also observed a relationship ($P < 0.001$) between FPT and routine measurement of STP concentrations on the surveyed farms. However, caution should be exercised when interpreting these results due to the small sample size.

Therefore, it is critical to monitor the quality of colostrum intended for feeding. Several factors can affect quality, but the farmer can positively influence them. These factors can be categorized as animal-related, such as parity and colostrum quantity, and environment-related, such as time from calving to milking and first feeding. Since most of these factors are already described in Study 1 (Section 3), this section will not elaborate on them further.

2.2.2 Quantity

Quantity refers to the amount of colostrum a calf should be fed after birth. Most studies indicated feeding 4 L of colostrum to a calf, but the recommendation has recently changed to a weight-related specification of 10.0–12.0% of the calf's body weight (Godden et al., 2019). However, the calf needs a certain amount of IgG and not a specific volume of liquid. This approach better meets calf requirements and TPI (Geiger, 2020). Nevertheless, one study found that feeding a colostrum amount equivalent to 8.5% of calf weight resulted in higher IgG absorption efficiency compared to the 10.0% specification (Conneely et al., 2014). It is important to note that insufficient intake during the first feeding can lead to FPT (Quigley et al., 2013). Additionally, Lora et al. (2018a) found that the risk of FPT decreased by 59.0% with each additional liter of colostrum (P = 0.028). In the study of Shivley et al. (2018), the serum IgG concentration increased by 0.57 mg mL^{-1} with each liter of colostrum fed in the first 24 h of life. This demonstrates that the amount of colostrum provided affects IgG absorption, with higher amounts leading to an increased serum IgG concentration. The aspect of quantity is explained in more detail in Section 3 (Study 1).

2.2.3 Quickness

In colostrum management, timing is crucial (Section 2.1.1; Figure 2.1.) Timing includes how quickly the calf is fed and how quickly the mother cow is milked after birth. In addition, the calf can only absorb the essential components for a short period (Figure 2.1) (Geiger, 2020). Therefore, it is important to feed colostrum promptly after birth. However, there is a wide variation in the interval between birth and first milking or feeding. According to Johnsen et al. (2019), this interval can range from zero to 20 h. The risk for FPT increases by 13.0% (P = 0.008) with each hour p.p., as reported by Lora et al. (2018a). Therefore, it is recommended to avoid such long time intervals between birth and first feeding. Furthermore, research has demonstrated that FPT is more prevalent in calves that receive colostrum later than 4 h after birth compared to those that receive it within the first 4 h (Beam et al., 2009). Additionally, Moore et al. (2005) discovered that the concentration of IgG in the colostrum decreases continuously. After 2 h p.p., colostrum contained 113.0 mg IgG mL^{-1}, whereas after 6 h p.p., only 83.2% of the previous IgG concentration was found. After 10 h p.p., 72.6% could still be detected. The IgG concentration decreases from the first to the second milking, and the required concentration of > 50.0 mg IgG mL^{-1} is mostly not reached beyond the first milking (Silva-Del-Río et al., 2017). As a consequence, the mother cow should be milked as soon as possible after birth, and the colostrum should be fed directly to the calf. In addition, the presence of sick cows or cows that are unable to be milked (e.g., milk fever) can also result in a delay in the milking process. Consequently, it is necessary to utilize reserves in an emergency situation. In the event that a calf does not drink voluntarily, one-time drenching with a tube by qualified personnel may be a viable alternative. However, the forced administration of food without a clinical background is prohibited according to § 3, point 9 of the German Animal Welfare Act. In the event that calves fail to accept colostrum within the initial hours of life, despite all efforts, an intervention should be considered (Ebert, 2006; BMJ, 2001). Quickness is also one of the environmental factors that influences the quality of colostrum and is explained in more detail in Study 1 (Section 3).

2.2.4 Quite Clean

Bacteria in colostrum can lead to FPT, which occurs when bacteria enter the calf's gastrointestinal tract, negatively affecting Ig uptake and inducing gut lining closure. The total plate counts (TPC; cfu mL^{-1}) or the total coliform counts (TCC; cfu mL^{-1}) are used to assess the contamination of colostrum by bacteria (Johnson et al., 2007). The TPC in colostrum should be < 100,000 cfu mL^{-1}, and that of TCC should be < 10,000 cfu mL^{-1} (McGuirk and Collins, 2004; Stewart et al., 2005). Bacterial contamination can occur during the milking (e.g., inadequate udder cleaning before milking) and feeding process due to environmental factors and poor hygiene (e.g., an unclean calving box). Feeding hygiene includes cleaning the feeding equipment before and after feeding (Stewart et al., 2005). Although no significant correlation was found between the number of cleaning procedures and TPC or TCC, the cleaning agent was significantly ($P < 0.05$) correlated with TPC. Using bleach or chlorhexidine before feeding resulted in odds of 0.054 (confidence interval (CI) = 0.01–0.57) of meeting the TPC specifications compared to cleaning with no disinfectant (Phipps et al., 2016). Bacteria may also be excreted from the mammary gland, resulting in high levels of bacteria even without an external source of contamination (Phipps et al., 2016). A study conducted by Buczinski et al. (2022) found a connection between the presence of contaminated feeding equipment on farms and elevated TPC and TCC levels in colostrum, an increased incidence of FPT, and a decline in overall health performance. It can be assumed that improvements are necessary with regard to the cleanliness of the equipment used for milking and feeding colostrum. In addition, the farmer, who may be assisting with the birth, gets dirty during the birth and feeds the calf without any subsequent hygiene measures. Because the calf needs to acclimate, the farmer often places the teat in the calf's mouth during the first feeding, which can lead to contamination.

Furthermore, warm room temperatures promote bacterial growth. Therefore, it is recommended to either directly feed or refrigerate the colostrum. For longer storage, farmers should freeze the colostrum. Pasteurization can reduce the number of pathogens but must be consistently implemented so that the Ig concentration is not negatively affected (Godden et al., 2019). An evaluation must also consider farm-specific factors (Abuelo et al., 2019).

2.2.5 Quantification

Quantification refers to the detection of IgG concentration in calf serum. One possible approach to quantification is to determine the concentration of STP in calves, as there is a significant positive correlation between serum IgG concentration and STP (Hampe and Wehrend, 2019). There are several direct and indirect methods to assess the concentration of IgG in calf serum.

Radial immunodiffusion (RID) is the gold standard among direct methods. Additionally, turbidimetric immunoassays (TIA) and enzyme-linked immunosorbent assays (ELISA) are direct methods for quantification. Other direct approaches include electrophoresis or split trehalase IgG quantification assays (STIGA). Indirect methods involve biochemical analysis of total protein and fractions and total protein concentrations determined by refractometry. Furthermore, Brix refractometers or a zinc sulfate turbidimetry test (ZST) can be used for indirect quantification (Cuttance et al., 2019; Souza et al., 2021). Laboratory methods are associated with challenges for farmers, as they cannot be conducted on-site. In numerous instances, the blood samples must be transmitted to the laboratory, which is a time-consuming process. Conversely, the refractometer enables direct measurement on the farm. There are no known studies on which quantification methods are used on German dairy farms. However, it can be postulated that the price of the device influences the purchase decision, with inexpensive devices such as colostrometers and simple refractometers being more prevalent than more expensive devices. The procedure and underlying methodology of the abovementioned measurement methods will be described in the context of the first study in Section 3.

2.3 Welfare and Health in Calves until Weaning

In 2022, approximately 2.25 million calves were kept in Germany up to the age of eight months (Federal Statistical Office, 2022), although the majority of male calves do not remain on farms for the entire duration. Over the past three years, the number of calves in Germany has remained relatively stable. In accordance with the *Tierschutz-Nutztierhaltungsverordnung* (Order on the protection of animals and the keeping of production animals; German designation: *TierSchuNutztV*), calves are defined as domestic cattle up to the age of six months (BMJ, 2001). Structural changes, similar to those in dairy farming, impact calf husbandry. This is due to the decrease in the number of farms, combined with increased farm size and specialization (Neuenfeldt et al., 2019), which affects the overall farm structure. In addition, there are regional differences in dairy farming and management throughout Germany, with various breeds being kept and farms varying greatly in size in terms of the number of animals and available farmland. These factors also impact calf husbandry, resulting in various management structures that must comply with legal requirements.

The feeding of calves with colostrum is also subject to legal regulations. According to the *TierSchuNutztV* regulations, calves must receive their first colostrum intake within 4 h of birth. Additionally, farmers are required to provide roughage from the 8^{th} day and water from the 14^{th} day of the calf's life. However, the quantity and quality of colostrum that a calf should be fed is not regulated by law (BMJ, 2001). Calves are typically weaned from milk feeders at 12 weeks of age. Male calves were usually sold between 14 and 28 days after birth (PraeRi, 2020). As of January 1, 2023, German legislation requires calves to be at least 28 days old before being transferred between farms in Germany. Previously, young animals could be transported starting from the fourteenth day of life (BMJ, 2001). Figure 2.2 illustrates that the previous transportation period (14^{th} day of life) falls within the immunological gap of the calf. In addition to this factor, stress-related influences due to transportation, as well as acclimatization to a new environment and farm-specific pathogens to which the calf was not previously exposed, must also be taken into account. The combination of these factors carries a significant risk of disease. Postponing the transportation period at least avoids the immunological gap. The cross-border transportation of calves from Germany within the European Union (EU) is still subject to the EU Animal Welfare Transport Regulation (EC) No. 1/2005 (EU, 2005).

Further, German legal requirements mandate that calves have the ability to lie down, stand up, and groom themselves. It must be guaranteed that every calf over two weeks of age has free access to an adequate quantity and quality of water at all times. Additionally, farmers must adhere to standards for floor design, lighting, climate management and social contact with other calves. Calves may be housed in individual pens for a maximum of two weeks, with dimensions of a minimum of 120 x 80 x 80 cm. For individual housing, it is crucial to consider larger box dimensions from the 2^{nd} to the 8^{th} week of life. After the 8^{th} week, group housing is required. In group housing, the floor size per calf is based on their live weight (BMJ, 2001). In Germany, calves are typically housed in igloos, open-front barns, or enclosed barn structures (Figure 2.3). Housing systems for animals are increasingly adopting igloos and open-front structures due to the positive impact of outdoor climate on animal health (PraeRi, 2020).

Figure 2.3 Examples of barn systems typically used in Germany for keeping calves: (**A**) igloos, (**B**) open-front barns and (**C**) enclosed barn structures.

The management of colostrum plays a significant role in animal health. In order to assess the quality of colostrum management in Germany, it is therefore essential to gain an understanding of the health status of calves in Germany. The PraeRi (2020) study offers valuable insights into animal health on German dairy farms, differentiating between the north, east, and south regions of Germany. According to the study, the perinatal mortality rate was 5.2% in the north, 6.1% in the east, and 4.0% in the south. Perinatal mortality refers to the proportion of stillborn calves and calves that die within the first 48 h p.p., in relation to all calves born. The study confirmed a previous report that larger farm sizes were associated with higher perinatal mortality (Gulliksen et al., 2009). However, the study's herd sizes of ≤ 20 and > 20 were relatively small and may not be applicable to farms with significantly larger numbers of animals (Gulliksen et al., 2009; Cuttance and Laven, 2019). Furthermore, previous studies demonstrated no significant correlation between herd size and perinatal mortality rate (Maryam Ansari-Lari, 2006; Mee et al., 2008). Postnatal mortality refers to the death of calves between the third day of life and the end of the third month. The mortality rate (median) for female offspring was 3.6% in the north, 5.9% in the east, and 0.0% in the south. However, the authors could not identify regional differences from a distribution analysis or establish a correlation between farm size and postnatal mortality rate. According to the PraeRi (2020) study, approximately one in ten calves in Germany do not survive beyond three months due to stillbirths and losses during rearing.

The PraeRi (2020) study and Hayer et al. (2021) reported the highest mortality rates 14 days p.p.. This time corresponds to the immunological gap of calves. Neonatal diarrhea was the most common cause of death in the PraeRi (2020) study, followed by respiratory disease, although this occurred more frequently in the second (29 to 56 days p.p.) and third month of life (57 to 84 days p.p.). Diarrhea and umbilical diseases were more common in the first two weeks of life than respiratory diseases, which mainly occurred from the fifth week of life. Umbilical or joint inflammation was mentioned as a reason for mortality to a very low extent during the first 14 days p.p.. Hayer et al. (2021) found that the morbidity rate for respiratory diseases varied from 0.0% to 70.0% on different farms. The minimum and maximum morbidity rates for diarrhea were 0.0%

and 100.0%, respectively. These results suggest that diarrhea is not a problem for all farms, but some are more affected than others (Hayer et al., 2021). The study revealed that hygiene, husbandry and feeding management problems can increase the incidence of multifactorial diseases. The mean operating prevalence of respiratory diseases was 4.5%, 5.2%, and 6.5% in the north, east, and south of Germany, respectively. A correlation was found between the frequent occurrence of these diseases and the housing in closed barns. In the northern region, umbilical infections were more prevalent at a rate of 26.6%, while diarrhea was more frequent at a rate of 14.3% in Germany's eastern part. There was no significant correlation between farm size and diarrheal diseases (PraeRi, 2020).

Separating sick calves from the rest of the herd can help prevent the spread of disease. A study conducted in Germany found that a significant percentage of participants in the north (33.9%), east (49.2%), and south (60.4%) do not isolate sick calves from the rest of the herd. The authors explained the high proportion in the south due to small groups of calves, making separation unimportant or impractical. If calves were separated, they were moved into individual stalls or igloos. In the eastern regions, separate sickrooms were used (PraeRi, 2020).

Diseases occur during the early stages of life because calves are born with low levels of Igs in their blood, making the period immediately after birth precarious. During this time, the calf lacks an immune system to defend itself against pathogens, resulting in high mortality rates for pre-weaned calves. Therefore, it is crucial to pay close attention to the rearing period, particularly colostrum management. Adequate colostrum management is essential for the calf to develop an immune system capable of defending against pathogens.

2.4 Management Factors to Improve Colostrum Management

Protocols and SOPs are essential components of quality assurance programs that help improve work processes and product quality (Gough and Hamrell, 2009). These components can also be applied to farms. Therefore, colostrum management can be optimized by implementing SOPs and improving work organization. Company-specific protocols outline what to do in particular situations, and within these protocols, SOPs explicitly state what to do per task (Gough and Hamrell, 2009; Barragan et al., 2016; Stup, 2017) and provide step-by-step instructions for employees to perform their tasks (Amare, 2012). Well-developed SOPs result in clearly defined and traceable tasks, clarify responsibilities and standardize work processes. Employee responsibilities are specified by summarizing all tasks, so SOPs provide employees with a well-defined task profile. As a result, the implementation of appropriate SOPs leads to savings in working time, improved quality of work (Buschsieweke et al., 2016), easier internal communication and shorter training sessions. These points are all relevant to colostrum management. However, it is important to note that familiarization with SOPs and training in specific steps still play a significant role in achieving these goals (Stup, 2017). Employees are more likely to perform and accept certain work tasks if they understand the reasons behind them. (Mills et al., 2020). Thus, SOPs, frequent feedback and focused training can help to create a productive and supportive work environment that enables the implementation of improved colostrum management.

When developing SOPs, it is recommended to involve employees. Essential to remember is the goal of creating a document that not only clearly explains the task but also considers all necessary aspects and assists the person performing the task. Document organization and format are critical. The form selected should be based on the complexity of the SOPs, as there are several options available. Consideration should be given to the number of decisions required within the scope of the task, as well as the number of stages and sub-stages (Figure 2.4) (Stup, 2017; Mills et al., 2020).

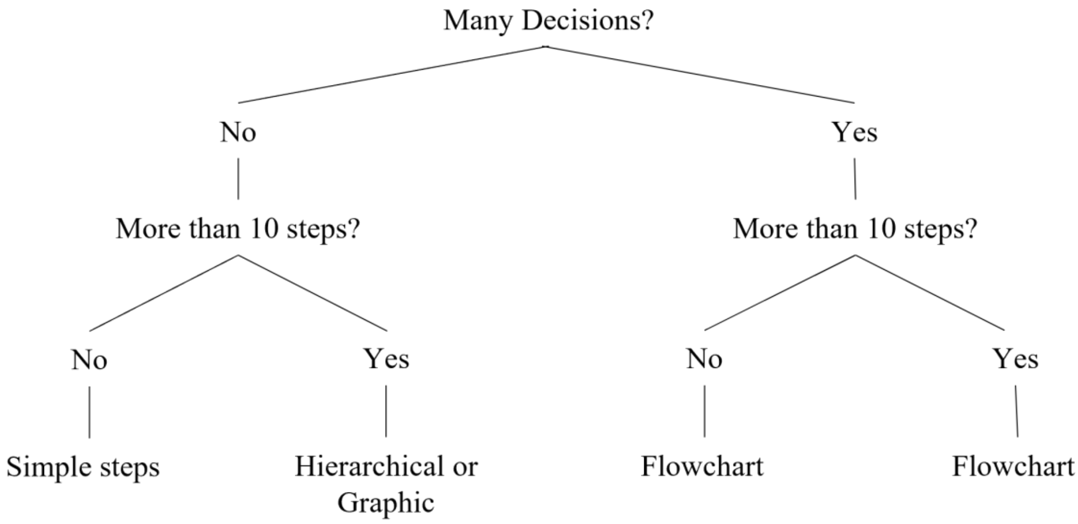

Figure 2.4 Decision tree for SOP format choices and criteria (adapted after Stup, 2017).

In describing routine tasks, simple language and a logical structure should be used. For complex tasks with more than ten steps but few decisions, hierarchical steps or a graphical format should be considered. In a hierarchical structure sub-items can be easily added to make them accessible to knowledgeable users. For experienced users, the simple defaults are sufficient, while new employees can refer to the more detailed sub-sections. If the SOP has more than ten steps and involves multiple decisions, a flowchart should be considered. The graphical representation can guide users through decisions and provide decision support for different alternatives (Stup, 2017). Pictures can enhance understanding, especially for employees who may face language barriers (Mills et al., 2020).

Despite their format, SOPs must contain specific elements. These include an informative title, clear identification of the SOP creator or manager and the start date for implementing the SOPs. If there are multiple SOPs, they should be numbered or structured (Stup, 2017). Additionally, it should be specified who will work with the SOPs and what qualifications are required for this role. When developing SOPs, it is important to consider factors such as training, relevant work experience and potential language barriers (Mills et al., 2020).

A seven-step process should be followed when creating SOPs to achieve optimal results. (Figure 2.5). Firstly, it is crucial to consider the purpose or intended usage of the SOP during its development. Specific goals can be defined for a variety of tasks based on the target values that are suitable within the framework of animal husbandry (Stup, 2017; Mills et al., 2020). The second step is to draft a comprehensive proposal that includes all necessary information. Next, employees who will subsequently have to work with the SOP should be involved in further development. Participants should provide feedback and recommendations for improvement based on the initial proposal to ensure clarity and completeness. After that, the input can be added to the document (Stup, 2017).

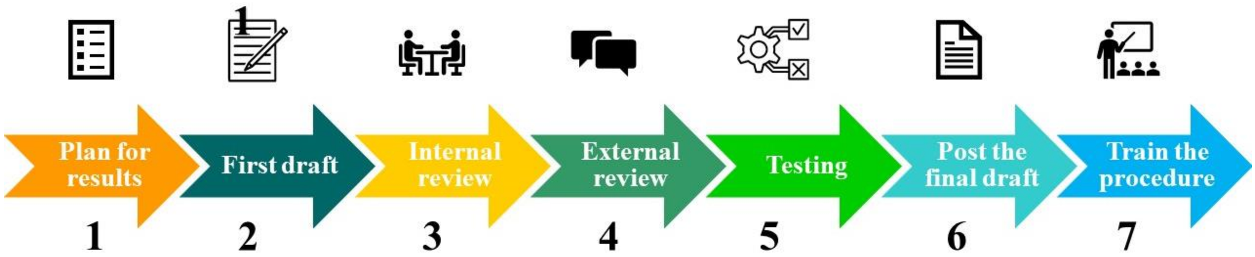

Figure 2.5 Seven steps for creating SOPs (Stup, 2017).

In addition, it is recommended to seek feedback from external consultants, such as the company veterinarian, in the fourth step. After integrating the external guidelines and information into the SOP, it should be tested by an individual who has not previously performed the task. This procedure ensures that the SOP is clear and understandable to new employees. Finally, the SOP should be revised again based on the feedback received. As a penultimate step, the final version of the SOP is created, posted in appropriate places, and distributed to employees. It is crucial that the specified work steps and associated processes are thoroughly understood and properly trained to ensure flawless and uniform performance (Stup, 2017).

In addition to SOPs and work organization, knowledge transfer plays a role in improving colostrum management. Knowledge transfer and knowledge utilization are supposed to justify the research efforts of many institutes and organizations. Therefore, it is not surprising that nowadays more attention is paid to the demand side. Unfortunately, the issue of knowledge utilization and transfer has not been sufficiently addressed in the field of livestock production (Kuipers et al., 2005). A promising use of knowledge requires the combination of findings and applications from animal science with social science approaches. An important aspect emerging from the research is the recognition that innovation consists of three dimensions (Kuipers et al., 2005):

1. Hardware: This includes the available technical equipment and zoological know-how, i.e., the concrete tools, technologies, and knowledge used in animal production.
2. Software: This is about the participants' intentions to work together and pursue the same goals. It concerns the social and interpersonal aspects that are of great importance for successful knowledge utilization and collaboration.
3. Orgware: This refers to the organizational structure in which the activities are embedded. A well-functioning organization and clear processes are critical to the efficient transfer and implementation of knowledge.

The combination of these three dimensions is critical to the successful application of knowledge in livestock production. It is not enough to focus only on technical equipment. To maximize the potential of knowledge, it is also necessary to optimize the conditions of the organizational framework and the cooperation between actors (Kuipers et al., 2005). The overarching goal of education and training is the pursuit of continuous learning. Learning involves the acquisition of knowledge, skills, competencies, attitudes and behaviors. It is essential that learning provides clear value to the organization/farm and serves as a tool to gain a competitive advantage. Employee training and development should focus on personal development and how it positively impacts business results. This impact includes increasing productivity and innovative ideas (Noe, 2017).

The third point that needs to be addressed for better colostrum management is the importance of data management. Increasing digitalization and advances in sensor technology have led to an increase in the number of assistance systems available on the market, bringing new and improved approaches to dairy farming (Sun et al., 2021). In calf husbandry, automation is becoming more prevalent, and assistance systems are being used more frequently, with the most widespread and advanced development being the use of automatic feeders for calf milk supply. Accelerometers are used to monitor changes in movement activity, which can provide insight into disease. Additionally, physiological parameters such as calf temperature can be recorded (Costa et al., 2021). Animal-specific data, including feeding and activity information, can provide farmers with valuable insights to improve management practices. Effective data management can simplify animal control, measure implementation, and improve quality monitoring. Veterinarians can use this information to identify health problems early and promote preventative health practices (Ellingsen et al., 2012; Gulliksen et al., 2009). Based on the aspects presented, colostrum management could generate data that can be applied to both calves and adult cows, adding value to farmers. Therefore, it is important to consider data collection in colostrum management.

This dissertation addresses the importance of colostrum management in calf rearing based on a literature overview (Section 2), a published review article, and a study (Sections 3 and 4). It becomes apparent that improvements in colostrum management are needed to strengthen and improve calf rearing. Consequently, the objective is to identify strategies for positive change in colostrum management. This includes re-evaluating strategies for work organization, knowledge transfer, and understanding the importance of data that can positively impact morbidity and mortality rates in calf rearing.

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3 Study 1

Review

Determining Immunoglobulin Content of Bovine Colostrum and Factors Affecting the Outcome: A Review

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Simple Summary

Colostrum management is essential in calf husbandry and strongly influences the calf. The immunoglobulin concentration denominates the quality of the colostrum, which is influenced by numerous factors. Therefore, the measurement of the immunoglobulin concentration is important. This review provides an overview of measurement methods for estimating the immunoglobulin concentration in bovine colostrum. In addition, influencing factors are identified, and their impact on the immunoglobulin concentration is discussed. Radial immunodiffusion and the Enzyme-linked immunosorbent assay are the most commonly used direct measurement methods. A refractometer and a colostrometer are practical indirect on-farm instruments that can be used to estimate the immunoglobulin concentration. External characteristics such as viscosity or color allow for an initial assessment but are too inaccurate. Animal-related factors such as colostrum yield, parity, and breed influence the immunoglobulin concentration. In addition, environmental factors are also important. The duration between birth and first feeding postpartum is important for the supply of colostrum with a sufficient immunoglobulin concentration. The influence of treatment methods such as freezing and thawing, on the other hand, depends strongly on the procedure and does not necessarily lead to a reduction in the immunoglobulin concentration. The influencing factors are complex and newer ones, such as genetics, have not yet been sufficiently investigated.

Abstract

The immunoglobulin concentration in bovine colostrum should be measured to ensure feeding with sufficient immunoglobulins (≥ 50.0 mg immunoglobulin G mL^{-1}). Adequate feeding prevents diseases, promotes development, and has a positive influence on the adult animal. Indirect and direct measurement methods are available for this purpose. Direct measurement methods cannot be easily used in practice; therefore, farmers use indirect methods such as a colostrometer and a refractometer. Many factors influence the immunoglobulin concentration of colostrum; some of them have already been intensively researched. In particular, lactation and temporal aspects play an essential role. Newer aspects such as dry period, seasonal influences, and genetics are gaining importance, but their impact on immunoglobulin content has not been sufficiently investigated. Developments are still needed, especially in data management. This review analyzes the outcome of different studies on indirect and direct measurement methods and discusses different factors influencing the immunoglobulin concentration of bovine colostrum.

Keywords: colostrum quality; refractometer; colostrometer; calf husbandry; radial immunodiffusion; colostrum management

3.1 Introduction

An adequate and timely supply of colostrum, within the first hours after birth, is essential for newborn calves and their later development [1,2]. The bovine placenta prevents the transfer of immunoglobulins (Ig) between the mother cow and her fetus. The placenta membranes have limited permeability, such that only gases and small molecules are able to pass through the membranes. Ig cannot pass through the membranes and because of that, calves are born with a minimal antibody level. However, the rapid intake of colostrum, which contains an adequate level of Ig, provides the calf with passive immunity [2].

The most important Ig in cow colostrum are immunoglobulin G (IgG) (with the subtypes IgG_1 and IgG_2), immunoglobulin A (IgA), and immunoglobulin M (IgM). IgG is the main component of cattle colostrum, accounting for 85.0% to 95.0% of the total Ig concentration. In colostrum, IgG_1 dominates, whereas the level of IgG_2 is much lower. IgM is the second most common Ig, followed by IgA [3–6]. The colostrum quality is an important factor in colostrum management, whereby the Ig concentration determines the quality of the colostrum. Generally, “good” colostrum has an IgG concentration ≥ 50.0 mg mL^{-1} [7,8]. Since the central part of Ig is IgG, the IgG concentration is often measured, rather than the total Ig concentration. A higher IgG_1 concentration in colostrum leads to a higher concentration of IgG_1 in the serum of calves [9]. However, the Ig concentration in colostrum can vary greatly from cow to cow, with various factors influencing the concentration. Thus, different studies have determined widely varying concentrations of Ig in the colostrum of cows [10,11]. Table 3.1 lists the quantity and ratio of Ig measured across different studies.

Table 3.1 Mean quantity and ratio of the Ig subtypes in bovine colostrum.

Ig	**IgG**		**IgM**	**IgA**	**Source**
	IgG_1	**IgG_2**			
Quantity (mg mL^{-1})	47.60	2.90	4.20	3.90	[3]
	75.00	1.90	4.90	4.40	[12]
	34.96	6.00	4.32	1.66	[13]
Ratio (%)	85.00–95.00		≤ 7.00	≤ 5.00	[4]

IgG = Immunoglobulin G; IgM = Immunoglobulin M; IgA = Immunoglobulin A

To prevent negative consequences, calves should consume colostrum as soon as possible after birth, particularly since the Ig concentration in the colostrum decreases significantly with each hour after birth [5,14]. Additionally, the permeability of the calf’s intestinal mucosa for Ig molecules decreases rapidly after 12 h, and usually disappears entirely on the second day of life [2]. Therefore, the timely feeding of colostrum ensures an adequate uptake of IgG_1 via the colostrum. An additional critical factor is the quantity of colostrum that the calf consumes during their first feeding after birth. Farmers should feed calves 10.0% to 12.0% of their body weight in colostrum in the first feeding to achieve a sufficient uptake [15]. The calves that consume 4 L of colostrum have a higher serum Ig concentration than the calves that consume 2 L of colostrum [16]. Moreover, calves supplied with colostrum containing a sufficient Ig concentration immediately after birth are less susceptible to diarrhea and lung diseases; these calves also develop better and show stronger growth [2]. Good colostrum management also leads to reduced morbidity and mortality in the first week of life [17]. In addition, the supply of colostrum influences further rearing; an inadequate supply leads to a later first calving age, as the required body weight is reached later [18]. The supply of colostrum also influences the adult animal. Cows that received an additional 2 L of colostrum as calves produced 1,349 kg more milk in the second lactation, compared to animals that received lower quantities of colostrum (9,516 ± 251 kg vs. 7,526 ± 252 kg, $P < 0.05$); however, the difference is smaller during the first lactation, although the calves who received 2 L still produced more milk (7,848 ± 253 kg vs. 7,526 ± 252 kg) [19]. In addition, the veterinary costs for calves that consume a greater volume of colostrum are lower than for calves that receive only 2 L. Calves with a lower colostrum intake require repeated treatments and monitoring to treat diseases, leading to increased veterinary costs [19].

An insufficient amount of IgG in the calf's blood 24 to 48 h after birth is referred to as a "Failure of Passive Transfer" (FPT) [20]. An IgG value < 10.0 mg mL^{-1} in the blood serum is often cited as an indicator of an FPT [21–24]; this FPT cut-off point is widely used to assess antibody uptake. An FPT increases economic losses. An insufficient supply of colostrum results in 60 to 80 € of extra costs per dairy or beef calf. If the prevalence of an FPT is high, these costs can rise to 95 € per dairy calf or 132 € per beef calf [25]. Nonetheless, a high Ig concentration in the colostrum does not automatically lead to a high Ig concentration in the calf's serum; different factors also influence the absorption of Ig [26,27], but these will not be discussed in this review.

For the reasons outlined above, controlling both the Ig concentration in the colostrum and colostrum intake is of great importance to calf rearing. The Ig concentration of the colostrum could be easily measured after milking. Nevertheless, only a few farms are undertaking this determination [2,3,26]. There are various direct and indirect measurement methods to estimate the concentration of Ig in colostrum. However, there is currently no direct measurement method that can be applied on farms; all the on-farm tools belong to the indirect measurement methods [27].

This article reviews the indirect and direct measurement methods to define the Ig concentration in colostrum. It compares the techniques in terms of their application under practical conditions and derives possible uses and development needs. In addition, the positive and negative aspects of the direct and indirect measurement methods, and the factors influencing the Ig concentration in colostrum, are discussed.

3.2 Methods for Measuring the Immunoglobulin Concentration of Colostrum

There are direct and indirect measurement methods to determine the Ig concentration in colostrum. Direct methods measure the Ig concentration, whereas indirect methods allow conclusions about the Ig concentration based on correlated properties. The indirect methods, for instance, are based on the change in the physical and chemical properties of colostrum as a liquid, whose specific gravity, density, or viscosity changes depending on the Ig concentration [2,3]. On-farm tools, whether direct or indirect, should be easy to use, effective, and accurate. In addition, results should be available quickly and the costs should be kept to a minimum [10,20]. We chose the following order in this review based on the frequency of the measurement methods in the literature used.

3.2.1 Direct Measurement Methods

RID and ELISA

Radial immunodiffusion (RID) is considered the gold standard for determining the Ig concentration in colostrum [10,22,28]. RID is an immunoprecipitation method for the quantitative determination of antigens in a sample. The antigen-containing samples (e.g., colostrum) are pipetted into the round punched holes of an antibody-containing agarose gel plate. The antigens diffuse circularly into the gel. This produces precipitate rings whose diameter (raised to the square) is proportional to the amount of antigen in the sample [29].

The Enzyme-linked immunosorbent assay (ELISA) is frequently used to quantify Ig in colostrum [30–32]. An ELISA is based on the antigen-antibody reaction and is a method for detecting and quantifying Ig. Immune complexes are formed, which additionally combine with enzymes. Based on this binding, the immune complexes can then be measured [29].

In a study by Gelsinger et al. (2015) [33], the IgG concentration in colostrum was measured with RID and an ELISA. Due to the high number of retests when the samples were analyzed using ELISA in this study, RID was considered the more consistent method. In addition, heating the colostrum resulted in a lower IgG concentration as measured using ELISA, whereas it did not induce any changes when measured using RID. However, there was a higher correlation between the values measured before and after heating using ELISA, compared to those measured using RID. The authors described this result as surprising, as the values measured by RID did not change after heating. In their view, this illustrates that the effect of heating on the protein composition in colostrum has a different impact on RID and ELISA [33].

Zobel et al. (2020) [34] also measured the IgG concentration in colostrum and found a lower test performance using ELISA, compared to RID. The ELISA results were also not repeatable using the RID method. These results are similar to the previously discussed research, despite using a different animal species (caprine). Based on their results, the authors do not recommend a direct comparison between the caprine IgG concentration recorded in different studies using different measurement methods (e.g., ELISA vs. RID) [34]. These findings differ from the work of Dunn et al. (2018) [35], in which the researchers assumed that the differences in correlations between different studies were also due to the specific kits used in each study. On average, the IgG concentrations measured using an ELISA were 1.8 times lower than those obtained using RID. A wide level of agreement (12.61–51.17) between RID and the ELISA was found in terms of the IgG concentration in colostrum. The authors suggested that this variation is due to the different dilutions of the samples. The samples were more diluted for the ELISA than for the RID samples [35]. Although the authors did not address sensitivity, it may be an additional reason for differences across the results of the two methods. Table 3.2 shows the different correlations between the RID and ELISA results that have been calculated in different studies. Based on these trends, the quality of the Ig may matter if there is no relationship.

Table 3.2 Relationships between RID and ELISA measurements of IgG concentration in colostrum across different studies.

Reported Parameter (*p*)	Significant	Colostrum	Source
r = 0.36 (= 0.01)	Yes	fresh bovine	[33]
r = 0.12 (= 0.42)	No	heated bovine	
P = 0.20 (< 0.0001)	No	frozen caprine	[34]
R^2 = 0.83 (< 0.001)	No	frozen bovine	[35]

r, *P* = correlation coefficient between IgG concentration measured by RID and ELISA;
R^2 = coefficient of determination

As mentioned above, in the literature, colostrum with a minimal IgG value ≥ 50.0 mg mL^{-1} is considered to be of good quality. This cut-off value is largely quoted for measurements with RID as a standard. As such, new limits may need to be set for the ELISA as a standard method [33]. None of the authors who used the ELISA experienced minimum values for the ELISA.

Even though RID and the ELISA are both very time-consuming, they are very sensitive laboratory methods [29]. Assuming calves should consume colostrum with a sufficient Ig concentration no later than 3 h after birth, these methods are unsuitable for rapid, practical use [1,23,33,36]. In addition, specific reagents with a limited shelf life and specific equipment are required to perform both procedures; therefore, the user must also be skilled in handling these materials; this is hardly feasible in practice [23,33,36,37]. Furthermore, the immunoprecipitated rings in simple RID are not stable, as the antibody concentration in the gel is constant. Therefore, evaluation must be performed at the exact correct time [29].

Large amounts of reagent-antibodies are required for RID; therefore, the cost of RID is relatively high [29]. The prices of the different assays vary greatly, ranging from 2.00 $ to 13.65 $ per test. For RID, the costs depend on the number of samples simultaneously tested since the standards must be determined each time [36]. For an ELISA test, prices also vary widely; according to German trade prices, the cost varies from 4 € to 7 € per test. In the future, the ELISA could be an economical alternative to RID [33], since many samples can be analyzed simultaneously, and the process can be almost entirely automated [38]. However, if only individual calvings are considered, it is questionable whether this is necessary or not.

Furthermore, the correlations in measurements across the studies differ greatly and do not show uniformity. These differences do not permit the formulation of any conclusions about whether the ELISA is suitable for adequately determining the Ig concentration in colostrum. Nevertheless, in research studies, ELISAs are commonly used to determine Ig concentration and could equally be considered the gold standard. A relatively high correlation was achieved in one study, in which the authors repeatedly referred to the influence of the specific test kits. Therefore, testing ELISA kits prior to their use should be considered.

Turbidimetric Immunoassay

Another method for determining the Ig concentration in colostrum is the turbidimetric immunoassay (TIA). A TIA is based on an antigen-antibody reaction and the resulting immune complexes that can absorb and scatter light. The light absorption is measured photometrically and is proportional to the antigen concentration over a wide range. More precisely, the increase in light attenuation (extinction) per minute is measured. Photometers and photometric analyzers can be used to perform a TIA [29].

Quigley et al. (2013) [8] additionally tested a TIA for measuring the IgG concentration in colostrum and were able to demonstrate a high correlation ($r = 0.87$; $P < 0.01$) between the IgG concentration in the colostrum determined by RID and the TIA. However, the TIA underestimated the IgG concentration compared to RID. Among the samples measured using the TIA, significantly more were below the limit of 50.0 mg mL^{-1} compared to those measured using RID [8]. Alley et al. (2012) [39] also calculated a very strong correlation between RID and the TIA (r = 0.99; $P < 0.05$) for measuring IgG concentration in colostrum [39].

In a comparison between a TIA and an ELISA, the IgG concentrations measured using the TIA (49.8 ± 26.3 mg mL^{-1}) were, on average, 21.0 mg mL^{-1} lower than the values measured using the ELISA (70.8 ± 27.7 mg mL^{-1}). It was not only the difference that proved to be statistically significant ($P < 0.0001$) but also the correlation between these two methods (r = 0.74; $P < 0.001$). There were clear differences in the direct comparison of the measured values despite the correlations, especially for samples with a high IgG concentration in the ELISA. The sensitivity of the TIA was 1.0 and the specificity 0.40. Sensitivity described the proportion of the TIA test results that indicated an inadequate (≤ 50.0 mg IgG mL^{-1}) colostral IgG concentration and was confirmed as such by the ELISA. The specificity described the proportion of test results using the TIA that indicates an adequate (> 50.0 mg IgG mL^{-1}) colostral IgG concentration and was confirmed as such by the ELISA [40]. In a study by Quigley et al. (2013) [8], the values determined using the TIA were lower than RID. Alley et al. (2012) [39] concluded that a TIA does not show better correlations with the direct measurement method ELISA than with established, less expensive, and indirect methods (e.g., colostrometer). Moreover, this is also a laboratory method that, similar to RID and the ELISA, cannot be used in practice without certain preconditions. The results of the TIA may also be affected by the non-IgG components. Quigley et al. (2013) [8] stated that components such as fat could affect the turbidity and thus, the result of a TIA. Furthermore, the cost-effectiveness of this method is questionable.

Infrared Spectroscopy

Infrared (IR) spectroscopy is based on transitions between vibrational levels. Molecules can carry out such vibrational transitions; however, two things must be fulfilled for this. Firstly, the light of a suitable wavelength must be irradiated. Secondly, a change in the dipole moment must be associated with the oscillation of the molecules. The latter condition is called IR activity. The spectral range that connects to visible light toward longer wavelengths (approximately 760–800 nm) is called “infrared”. This range is divided into the near IR (NIR, 760–3000 nm), the mid-IR (MIR, approximately 3–30 µm), and the far IR (FIR, approximately 30–1,000 µm). The division into these three ranges is made because different forms of vibration of the molecules occur in the different ranges [41].

Elsohaby et al. (2018) [42] observed a correlation of r = 0.88 between the measured IgG concentration of RID and IR in fresh colostrum. For heated colostrum, the correlations varied between r = 0.85 and r = 0.70, depending on the period and temperature. The lowest correlation was found at 63°C/60 min (r = 0.70). For IR and fresh colostrum, the sensitivity and specificity were 0.82 and 1.00, respectively, (cut-off point of 50.0 mg IgG mL^{-1}) and the accuracy was 0.92. All three values are affected by heating; therefore, the sensitivity, specificity, and accuracy at 63°C/60 min were 0.63, 0.83, and 0.80, respectively. Heating colostrum at 60°C for 30 min or 60 min does not seem to affect the IR results. However, when they raised the temperature to 63°C for the same amount of time, inaccuracies in the IgG concentration (measured using IR) were observed. Another study investigated the potential of transmission infrared (TIR) spectroscopy to determine IgG concentration in colostrum from dairy and beef cows. A total of 430 samples were analyzed and RID was the comparative method. The correlation measured with RID and TIR between the IgG concentration of two different colostrum sets was 0.84 and 0.96, respectively [43]. The correlations between RID and TIR concerning the IgG concentration are, in part, higher than the correlations measured between RID and the colostrometer [5,7,31,44] or the refractometer [11,20,34,45]. Another study determined good agreement between the different statistical parameters calculated for RID and IR. The correlation between these two methods was 0.91.

Furthermore, a sensitivity of 0.90, a specificity of 0.92 and an accuracy of 0.90 were calculated if IR is used regularly. Using a cut-off value of < 50.0 mg IgG $mL^{-1,}$ IR classified eight colostrum samples as false positives and 16 samples as false negatives (n = 250) [46]. IR spectroscopy cannot be used in practice without further prerequisites, as this is also a laboratory method. However, the method appears to be more accurate than indirect measuring instruments, and the results are promising for future studies.

Nevertheless, performing IR requires expensive equipment. A spectrometer with which the IR spectra are acquired can cost up to 2,000 € depending on the equipment. These are certainly laboratory devices that will not find purchase applications on farms.

3.2.2 Indirect Measurement Methods

Refractometer

An indirect tool for the measurement of the Ig concentration in colostrum is the refractometer, which measures the concentration of dissolved substances in liquids. A refractometer can be used to determine the refractive index, permitting conclusions about the density of the liquid to be made. The concentration of the ingredients (e.g., Ig) influences the density of the liquid (e.g., colostrum). As such, by measuring the density, conclusions can be drawn about the concentration of the ingredients [8,47]. The density of a liquid depends on its temperature, with density decreasing with an increasing temperature [48]. Therefore, the temperature of the colostrum can influence the result. Most refractometers include automatic compensation for the temperature [49].

Refractometers provide results expressed as %Brix, wherein the Brix value corresponds to the proportion of dry matter percentage [8,47].

A differentiation is made between optical and digital refractometers. Optical refractometers must be held in the direction of a light source, then the measured value can be read in %Brix. Digital refractometers automatically display the result in digital form. Before the Ig concentration in colostrum was measured, refractometers were mainly used to measure the Ig levels in blood serum [50,51]. Refractometers can, therefore, also be used to examine the possibility of an FPT [52].

Some studies have investigated the suitability of both optical and digital refractometers for determining the IgG concentration in colostrum [11,20,34], whereas others have only used one type of refractometer [7,8,42,45]. In studies analyzing the ability of refractometers to determine the Ig concentration in colostrum, the sensitivity ranged from 0.56 to 1.0 for optical refractometers and from 0.66 to 1.0 for digital refractometers. Optical refractometers had specificities of 0.63 to 0.90, whereas digital refractometers had specificities of 0.65 to 0.83. Sensitivities varied more in optical refractometers than digital refractometers. For both types of refractometers, the ranges in values for specificity and sensitivity were wide. Table 3.3 outlines the different sensitivities, specificities, and correlations from the studies included in this review.

Table 3.3 Sensitivities (Se), specificities (Sp), and correlations for measurements of IgG concentration in different studies with digital and optical refractometers in comparison to the gold standard.

Refractometer	Standard	Se	Sp	Correlation	R^2	Special Features	Source
Digital	RID	0.93	0.80	0.73 *	0.53	fresh colostrum for Se and Sp	[20] [1]
Optical		0.91	0.85	0.71 *	0.51	frozen colostrum for correlation	
Digital	RID	0.79	0.69	n. d.	n. d.	Incubated in water baths to maintain the optimum temperature	[10] [1]
Optical		0.56	0.90				
Digital	RID	0.82	0.81	0.60*	n. d.	n. d.	[5] [1]
Optical		0.80	0.83	0.60*			
Digital	RID	0.74	0.80	0.72*	n. d.	frozen colostrum	[11] [1]
Optical		0.73	0.80	0.71*			
Digital	RID	1.00	0.66	0.74	n. d.	frozen and unheated colostrum	[42] [1]
Optical		1.00	0.63	0.73			
Digital	RID	0.97	0.61	0.75		frozen and heated at 60°C for 30 min	
Optical		0.97	0.65	0.73			
Digital	RID	0.97	0.65	0.71		frozen and heated at 60°C for 60 min	
Optical		0.97	0.68	0.70			
Digital	RID	0.90	0.38	0.48		frozen and heated at 63°C for 30 min	
Optical		0.90	0.38	0.50			
Digital	RID	0.88	0.39	0.58		frozen and heated at 63°C for 60 min	
Optical		0.88	0.39	0.57			
Digital	RID	0.75	0.78	n. d.	0.41	fresh colostrum for refractometer frozen colostrum for the RID	[1] [1]
Digital	RID	0.66	0.83	0.64	0.43	frozen colostrum	[7] [1]
Digital	RID	1.00	0.65	n. d.	n. d.	fresh colostrum for refractometer frozen colostrum for the RID	[53] [1]
Digital	RID	0.84	0.79	0.71*	n. d.	frozen colostrum	[45] [1]
Digital	RID	0.84	0.79	0.68–0.76	n. d.	frozen colostrum	[54] [2]
Optical	RID	0.93	0.66	0.75**	0.56	frozen colostrum	[8] [1]
Optical	ELISA	0.86	0.85	n. d.	0.43	frozen colostrum for ELISA na for refractometer	[31] [1]

n. d.= no data; R^2 = coefficient of determination; [1]Cut-off point of ≥ 50 mg IgG mL^{-1} for colostrum of good quality; [2]Cut-off point of ≥ 150 mg IgG mL^{-1} for colostrum of good quality; *P < 0.001; **P < 0.01; RID = Radial immunodiffusion; ELISA = Enzyme-linked immunosorbent assay

Most studies have demonstrated correlations of around 0.7 between measurements obtained via RID and both optical and digital refractometers [11,20,34,45]. Elsohaby et al. (2017) [11] and Bielmann et al. (2010) [20] determined higher correlations between the concentrations determined via RID and a digital refractometer than RID and an optical refractometer. On the one hand, Zobel et al. (2020) [34] determined a higher correlation for the optical refractometer (r = 0.73) and RID than the digital refractometer. This value was confirmed by Elsohaby et al. (2018) [42] (n = 60), whereas Quigley et al. (2013) [8] calculated a slightly higher correlation (r = 0.75; n = 183). On the other hand, Bartier et al. (2015) [7] showed a lower correlation (r = 0.64) between the IgG concentrations detected using RID and a digital refractometer (n = 460). Using the ELISA as a standard, Lemberskiy-Kuzin et al. (2019) [31] validated an optical refractometer; they found R^2 values of 0.43. On the other hand, in studies by Bielmann et al. (2010) [20] and Zobel et al. (2020) [34], R^2 values of 0.56 and 0.53, respectively, were calculated.

Bielmann et al. (2010) [20] and Zobel et al. (2020) [34] found high correlations between the Ig concentrations determined via the two refractometer types. Bielmann et al. (2010) [20] noted a correlation of 0.98 ($P < 0.001$) for fresh colostrum, and 0.97 ($P < 0.001$) for frozen colostrum. For fresh colostrum, Zobel et al. (2020) [34] found a similar correlation between measurements taken via a digital and optical refractometer (r = 0.99). Additionally, Bartens et al. (2016) [10] investigated the intra-observer reliability of both types of refractometers. The intraclass correlation coefficients were 0.97 (CI = 0.95–0.98) and 0.98 (CI = 0.97–0.99) for the optical and digital refractometer, respectively.

Elsohaby et al. (2018) [42] noted stronger correlations between the IgG concentration measured using RID and an optical and digital refractometer for unheated colostrum (r = 0.73 and 0.74) than for colostrum heated to 63°C for 30 min or 60 min.

Based on their study, Bielmann et al. (2010) [20] established an optimal threshold of 22% Brix to detect colostrum with an IgG concentration ≥ 50.0 mg Ig mL^{-1}. Further studies have provided different cut-off points for refractometers. For instance, Bartens et al. (2016) [10] calculated an optimized cut-off point of 27.0% Brix for an optical refractometer; this value is similar to that proposed by Dunn et al. (2018) (27.3% Brix) [35]. Bartens et al. (2016) [10] obtained a cut-off point of 23.4% Brix for a digital refractometer; comparable values were found in studies by Bartier et al. (2015) [7] (23.0% Brix), Bielmann et al. (2010) [20] (22.0% Brix), Chigerwe et al. (2008) [1] (22.0% Brix), and Elsohaby et al. (2017) [11] (24% Brix). Nevertheless, other studies also describe lower cut-off points, such as 20.6% Brix and 21.9% Brix [5,45]. Across all studies, the most commonly used cut-off point is ≥ 22.0% Brix; however, a meta-analysis of the accuracy of refractometers in detecting colostrum with an IgG concentration ≥ 50.0 mg mL^{-1} demonstrated that a cut-off point of 22.0% Brix leads to a significant number of false-negative samples [55]. This prevalence of false negatives seems to be particularly high when the prevalence of good colostrum is high. As a result, a cut-off point of 22.0% Brix can lead to poor colostrum ratings, even when the sample contains a sufficient IgG level. Buczinski et al. (2016) [55] consider a Brix value < 18.0% Brix useful for filtering out colostrum with an insufficient Ig concentration, whereas colostrum in the range of 18.0–22.0% Brix should be considered suspect, and colostrum with a Brix value ≥ 22.0% Brix should be used.

Rayburn et al. (2019) [53] used a digital refractometer to examine the IgG concentration in colostrum and transition milk up to the fifth milking. For the first milking, a cut-off point of 19.3% Brix was used to detect colostrum with IgG levels of at least 50.0 mg mL^{-1}; a sensitivity of 0.83 and specificity of 0.51 were obtained. For the second milking, a cut-off point of 14.0% Brix was chosen as a value for 25.0 mg IgG mL^{-1} milk, whereas a cut-off point of 12.3% Brix (10.0 mg IgG mL^{-1}) was defined for the third milking. As the number of milkings increases, the IgG concentration in the colostrum decreases, so the detection of the IgG concentration also becomes increasingly difficult. At low IgG levels, the lower detection limit is reached. When the IgG concentration is this low, colostrum should no longer be used for the first feeding of newborn calves. According to the calculated sensitivities (0.51) and the area under the curve (0.51), the authors consider refractometers to no longer be valid as of the fourth milking. In the fifth milking, an IgG concentration of only 10.0 mg mL^{-1} was found. Based on their results, the authors recommend using a digital refractometer for the first, second, and third milkings p.p. [53].

Refractometers are break resistant and only require a few drops of colostrum to perform measurements [10,50,51]. All in all, they are cheap (25–200 €, German trade prices) and a quick tool that can be used with little additional equipment or training [8,47]. Nevertheless, the refractive index of milk and colostrum depends on the concentration and composition of the total solids. More specifically, the volume and distribution of protein in the colostrum, as well as the fat content and casein micelles, affect the accuracy of measurements taken using refractometers [56]. As such, higher correlations cannot be achieved with respect to the gold standard (RID).

Colostrometer

Another tool to estimate the Ig concentration in colostrum is a colostrometer (hydrometer). The colostrometer consists of a measuring cylinder, spindle, and a float, allowing conclusions about the specific gravity due to its displacement. The density correlates with the Ig concentration of the colostrum. Based on this correlation, the density measured with the colostrometer can conclude the Ig concentration. The float contains a scale of different colored areas indicating three different levels of Ig concentration in colostrum (green: > 50.0 mg Ig mL^{-1}, yellow: 20.0–50.0 mg Ig mL^{-1}, red: < 20.0 mg Ig mL^{-1}) [57].

The colostrometer was first described by Fleenor and Stott (1980) [57], who showed the linear relationship between the total Ig concentration and the specific gravity of colostrum.

Bartens et al. (2016) [10] tested two hydrometers from different companies for accuracy and precision in measuring IgG in colostrum with regard to the optimum sample temperature (20°C vs. 37°C). The cut-off points specified by the manufacturers for “good” colostrum (> 50.0 mg IgG mL^{-1} obtained with RID) were 1.047 and 1.045 for the two different hydrometers adapted to 20°C and 37°C, respectively. Furthermore, the optimal cut-off points were determined independently of the manufacturers' specifications. An optimized cut-off point of 1.055 was evaluated using a receiver operating characteristic curve for the hydrometer used at 20°C and 1.054 for the hydrometer used at 37°C [10]. In another study, different cut-off points for the colostrometer were tested to detect colostrum containing 50.0 mg IgG mL^{-1}. Specificity, accuracy, sensitivity, positive predictive value, and negative predictive value were compared. The highest combined sensitivity and specificity for detecting adequate colostrum defined using RID occurred at a cut-off point of 80.0 mg IgG mL^{-1}. The sensitivity was 0.84 and the specificity was 0.77. At this cut-off point, the colostrometer had an accuracy of 0.80 [7]. In contrast to the previously described study, Chigerwe et al. (2008) [1] determined an optimal cut-off point for two different hydrometers. For the first colostrometer, cut-off points were investigated in ten steps from ≤ 10.0 mg mL^{-1} to ≥ 140.0 mg mL^{-1}. At the optimal cut-off point of 70.0 mg mL^{-1}, the sensitivity and the specificity were 0.75 and 0.78, respectively. For the second colostrometer, they surveyed cut-off points in steps of 12.5 from ≤ 25.0 mg mL^{-1} to ≥ 125.0 mg mL^{-1}. An optimal cut-off point of 87.5 mg mL^{-1} was calculated, which was achieved at a sensitivity and specificity of 0.75 and 0.66 [1]. The authors stated that instrument-specific cut-off points should be defined within the scope of these variations, even with the same instruments. For the first colostrometer, they recommend a range of 60.0 mg mL^{-1} to 90.0 mg mL^{-1} for possible cut-off points. The second colostrometer should have a range from 75.0 mg mL^{-1} to 100.0 mg mL^{-1} [1]. Table 3.4 summarizes the different sensitivities, specificities, and correlations of the colostrometer studies.

Table 3.4 Sensitivities (Se), specificities (Sp), and correlations for measurements of IgG concentration in different studies with the colostrometer compared to the gold standard.

Standard	Se	Sp	Correlation	Source
RID	n. d.	n. d.	0.43	[58] [1]
RID	0.75	0.78	n. d.	[1] [1]
RID	0.76	0.66	n. d.	[1] [1]
RID	n. d.	n. d.	0.67	[59] [1]
RID	n. d.	n. d.	0.79	[44] [1]
RID	0.84	0.77	0.77	[7] [1]
RID	0.73	0.72	n. d.	[10] [1]
RID	0.71	0.61	n. d.	[10] [1]
RID	0.69	0.81	0.57	[5] [1]
RID	n. d.	n. d.	0.83	[34] [1]
ELISA	0.93	0.69	n. d.	[31] [1]
Refractometer	n. d.	n. d.	0.89	[60] [1]
Refractometer	n. d.	n. d.	0.86	[44] [1]

n. d. = no data. [1]Cut-off point of ≥ 50.0 mg IgG mL^{-1} for colostrum of good quality; RID = Radial immunodiffusion; ELISA = Enzyme-linked immunosorbent assay

In a study by Bartens et al. (2016) [10], the second utilized hydrometer had a similar sensitivity but a lower specificity than the first hydrometer. Based on these values, the accuracy for hydrometer one was higher than for hydrometer two. The authors stated that hydrometer one could be used directly after milking, whereas the colostrum for hydrometer two had to be cooled down first. They speculated that the results would have differed if both hydrometers had been used at the same temperature [10]. In 1991, Mechor and Gröhn [61] investigated the influence of temperature on the results of colostrometer readings. They collected 25 colostrum samples from Holstein-Friesian cows and measured the Ig concentration using a colostrometer. The colostrum temperature was increased in 5°C steps from zero to 40°C and the Ig concentration was measured at each step. They found a significant effect ($P < 0.01$) of temperature on the readings. The readings varied by 0.8 mg mL^{-1} between temperature levels. The regression coefficients for colostrum and the sample temperature tended to rise with the increasing concentration category. The effect of the sample temperature on colostrometer results depends on the concentration [61].

The relationship between the IgG concentration in colostrum measured using a colostrometer and a refractometer has been assessed in some studies. Morrill et al. (2012) [44] confirmed the correlation determined by Hassan et al. (2020) [60] for the IgG concentration measured using a refractometer and a colostrometer.

However, a colostrometer depends on the ambient temperature and the results are only comparable at a colostrum sample temperature of 20–21°C [52]. Compared to the refractometer, the colostrometer is not break resistant and challenging to clean but cheaper (20–30 €, German trade prices) [10,62]. The results of the colostrometer also depend on the dry matter content, where a higher solid content or more fat in the colostrum leads to higher specific gravity [52].

Split Trehalase IgG Quantification Assay and Zinc Sulfate Turbidity Test

Drikic et al. (2018) [27] tested a split trehalase IgG quantification assay (STIGA) for the measurement of IgG in colostrum. The results were compared with the gold standard RID and its potential as an on-farm tool was described. A STIGA is based on the enzyme trehalase (TreA), which converts trehalose into glucose. TreA splits into two non-functional fragments ($TreA^N$ and $TreA^C$). The fragments fuse with protein-G, which specifically binds to IgG and, thus, acts as a sensor for IgG. If the fusion proteins are incubated with colostrum, binding with the IgG contained in the colostrum occurs. TreA is reactivated and glucose is formed from trehalose. The glucose formed can be detected with a colorimetric assay or a glucometer. Based on the glucose, the IgG concentration in the colostrum can then be indirectly inferred [27,64].

Dirkic et al. (2018) [27] performed a colorimetric assay (STIGA) and a glucometer test strip-based assay ($STIGA^{FIELD}$). The authors found a correlation of IgG concentration for dairy breed colostrum measured using RID and a STIGA of r = 0.72. The correlation for beef colostrum was similarly high at r = 0.73. The highest sensitivity and specificity for dairy breeds were found at an optical density cut-point of 0.9. For colostrum from beef breeds, the highest sensitivity (0.83) and specificity (0.90) were recorded at an optical density of 0.8. The STIGA identified 23.0% of the dairy colostrum samples as poor, whereas RID recognized 28.3%. Of the beef cow samples, 23.4% were defined as poor using a STIGA and 18.8% using RID. The correlation between the IgG concentration measured with RID and glucose concentration measured via glucometer ($STIGA^{FIELD}$) is r = 0.7 for dairy colostrum and r = 0.94 for beef colostrum.

Compared to the indirect methods, a refractometer and a colostrometer, the STIGA shows comparable sensitivity and improved specificity. The STIGA needs 90 min until a result is available. The authors also point out that fewer laboratory utensils are required, and that the procedure can be automated [27]. In addition, a user-friendly method ($STIGA^{FIELD}$) was tested, which, according to the authors, could also be used on farms. This variant does not require laboratory equipment or trained personnel.

Furthermore, strong correlations between the $STIGA^{FIELD}$ and RID were determined. Therefore, the authors consider it a promising method to be tested under practical conditions [27]. A glucometer test strip-based assay was used to determine the concentration. This assay is commercially available for less than 25 € per test and represents a cost-effective variant.

In the zinc sulfate turbidimetry (ZST) test, salts are formed by chemical combinations of heavier globulins and trace metal ions. The salts precipitate and the interpretation can be made visually or with spectrophotometry. Visually, the test can be performed within 30 to 60 min. The concentration of IgG is proportional to turbidity. Even though a spectrophotometer is more precise, it takes longer to perform such a measurement. The measured optical density is compared with a standard curve [64].

Dunn et al. (2018) [35] tested ZST to approximate the IgG concentration in serum samples of ten Holstein-Friesian and ten Limousine × Holstein-Friesian cows. They found a significant ($P < 0.001$) positive correlation between the IgG concentration in serum samples measured using RID ($R^2 = 0.78$) as well as the ELISA ($R^2 = 0.77$) and IgG concentration measured using ZST. Pompermayer et al. (2019) [65] tested the ZST in practice and the laboratory to detect an FPT in foals. Although blood rather than colostrum was tested for the IgG concentration, conclusions about the practicality of ZST are possible. The ZST test was stored at the farm at room temperature, which varied considerably within the experiment (−1.2°C to 32.3 °C). For comparison, a ZST test and a RID test were also performed in the laboratory. The number of false positives in the ZST on-farm tests was five times higher than in the laboratory samples.

The authors attribute this primarily to the difference in temperature, as ZST is temperature dependent. The study calculated a correlation of 0.92 ($P < 0.0001$) between the temperature and the turbidity of the zinc sulfate solution after reaction with serum. They suggest that the low temperature slows down the reaction [65]. The strong temperature dependence should be considered negative for practical use since the number of false-positive results should be kept as low as possible. The authors suggest warming the blood to 30–37°C. However, these findings should be confirmed regarding the IgG concentration in the colostrum samples to obtain more precise data. The practical use, especially concerning temperature, should be further considered in future studies. In addition, the cost of a spectrometer is very high at up to 2,000 €. Turbidity can also be assessed manually, but this assessment is inaccurate.

External Characteristics

Colostrum comes in a variety of colors, ranging from dark brown to yellow to white. The color of the colostrum is often linked to its Ig concentration, with lighter milk signifying a lower density [66]. The same applies to viscosity, the flow resistance of a liquid, which is often used as an indirect indicator of the Ig concentration. It has long been assumed that colostrum with a higher viscosity has a higher concentration of Ig. Due to that, viscosity has been measured visually for a long time as an indicator of the colostrum Ig concentration. The simplest method is the visual assessment of the flow properties, although this is the least accurate method. There are measuring instruments that can assess or directly measure the viscosity of the colostrum. However, within the scope of this review, only a few studies were found that examined the relationship between viscosity and Ig concentration in colostrum [47].

Different viscometers can determine viscosity; this includes, for example, an outlet funnel [5,47]. When using an outlet funnel, the time until a defined volume of colostrum runs out entirely is stopped. Based on the transit time, the viscosity of the colostrum can be inferred [5]. An outlet funnel costs around 15 €. Kritzinger (2017) [5] demonstrated, in his study with 124 Simmental cows, a positive correlation ($r = 0.42$) between funnel run time and IgG concentration in colostrum measured using RID. According to his results, colostrum (100.0 mL) with a transit time longer than 24 s should indicate an IgG concentration of > 50.0 mg mL^{-1}. The specificity and sensitivity of the method were 0.78 and 0.74, respectively.

Hassan et al. (2020) [60] found a significant correlation ($r = 0.58$; $P < 0.05$) between the viscosity measured using an electronic viscometer (dynamic viscosity) and the IgG concentration in colostrum determined using the colostrometer. A significant correlation of $r = 0.74$ ($P < 0.05$) was obtained compared with a digital refractometer. In addition to determining the viscosity using an electronic viscometer, the viscosity was also assessed visually, and the colostrum was divided into the following categories: watery, liquid, and thick. Significant correlations were found between the visual viscosity and the IgG concentration measured using the digital refractometer and the colostrometer. For the concentration in mg mL^{-1} estimated using the colostrometer and the visual viscosity, the correlation was $r = 0.90$ ($P < 0.05$). The correlation between the Brix value and dynamic viscosity is given as $r = 0.84$ ($P < 0.05$). A significant correlation ($r = 0.63$; $P < 0.05$) was also found between the visual viscosity and the dynamic viscosity [60]. Another study showed no correlation between the IgG concentration and the liquidness or thickness of the colostrum [58].

Chigerwe et al. (2008) [1] considered the colostrum yield to indicate a sufficient concentration of IgG. They used a digital scale to determine the amount of the first milking in 171 cows. The mean colostrum weight of the first milking was 7.4 ± 3.9 kg. The cut-off point calculated by sensitivity (0.42) and specificity (0.74) for the determination of colostrum with < 50.0 mg mL^{-1} is given as 8.5 kg. With this cut-off point, 56 of the 171 colostrum samples were classified as adequate. Due to the low sensitivity, the authors do not recommend the weight of colostrum as a suitable indicator for colostrum with sufficient IgG [1].

A study by Gross et al. (2014) [66] demonstrated the relationship between colostral IgG concentration and color measurement for 117 colostrum samples from Holstein-Friesian cows. No significant correlation (r = −0.08; *P* = 0.40) could be found between the color measurement and the IgG concentration. The lactation did not influence the relationship between the two parameters. To classify colostrum into high- and low-quality, the following three threshold values were set: 50.0 mg mL^{-1}, 75.0 mg mL^{-1}, and 100.0 mg IgG mL^{-1}. The highest sensitivity (0.50), specificity (0.50), and negative predicted value (0.88) were calculated at the threshold of 50.0 mg IgG mL^{-1}. According to the authors, color measurement is a method to conclude the IgG concentration. However, the inference of IgG concentration with the visually perceived colorfulness (chroma value G) is insufficient and does not improve over other instruments, such as the refractometer [66]. The color of the colostrum is a very subjective factor for concluding the IgG concentration of the colostrum [58]. If the assessment is performed visually without technical support, the result depends heavily on the performing person and their experience. Therefore, farmers should not rely solely on this assessment when providing calves with sufficient colostrum. By using measuring devices such as a spectrophotometer, the color measurement could offer an additional way of determining the Ig concentration in the future, next to the colostrometer and refractometer [66]. Figure 3.1 gives a final overview of the measurement methods and tools described in this review.

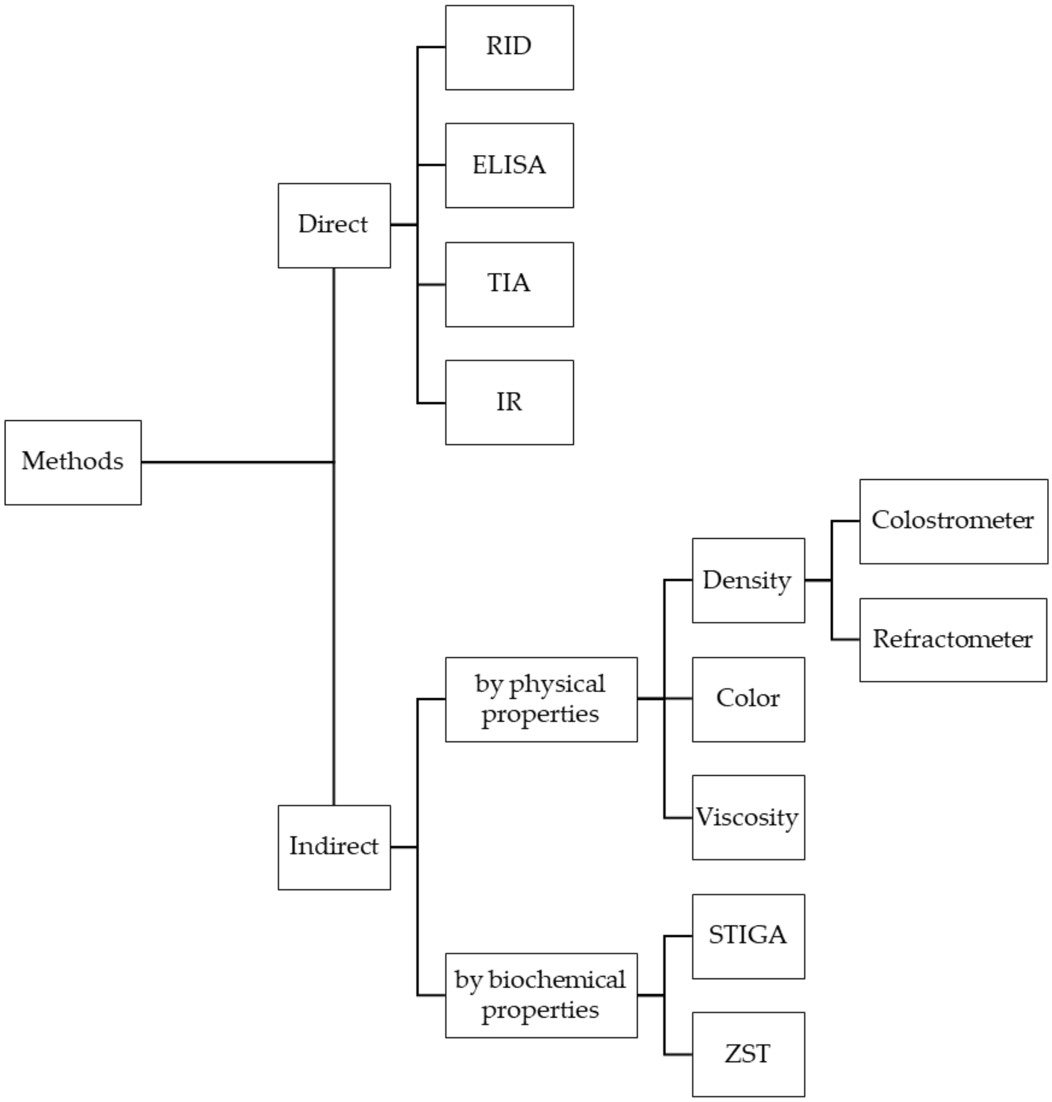

Figure 3.1 Overview chart of the direct and indirect methods for determining Ig concentration in bovine colostrum presented in section 3.2 (RID = Radial immunodiffusion; ELISA = Enzyme-linked immunosorbent assay; TIA = Turbidimetric immunoassay; IR = Infrared; STIGA = Split trehalase IgG quantification assay; ZST = Zinc sulfate turbidity test).

3.2.3 Dissemination of the Methods

The control of colostrum quality, i.e., the determination of Ig concentration, does not seem to be widespread in dairy farming. In a survey conducted by Klein-Jöbstl et al. in 2015 [26], 1,287 Austrian farmers participated and 78.7% stated that they do not verify the Ig concentration in colostrum before feeding. Only 20.8% of the respondents tested the Ig concentration in the colostrum on their farms, and 0.5% did not answer the question. The test is mainly performed by visual observations (86.1%) [26]. In a survey from Germany, 92.9% of the respondents (n = 42) reported controlling colostrum intake; however, only 23.8% noted the Ig concentration of the colostrum [67]. The result is similar to the Austrian study.

3.3 Factors Associated with Immunoglobulin Concentration in Colostrum

The variation of Ig concentration in colostrum is high and influenced by several factors. For optimal colostrum management, it is helpful to know which factors influence the Ig concentration and to what extent. It is also important to understand how these parameters can be employed to improve the Ig concentration in colostrum. To feed calves colostrum with a high Ig concentration, the reducing factors that lower the Ig concentration should be avoided as far as possible. A distinction can be made between animal-related and environmental-related factors. In the following, the factors and their influence will be examined in more detail.

3.3.1 Animal-Related Factors

Colostrum Yield

In their studies, Silva-Del-Rio et al. (2017) [68] and Cabral et al. (2016) [69] demonstrated a negative correlation between colostrum yield and IgG concentration. The negative correlation of r = −0.42 in Cabral et al. (2016) [69] is slightly higher than in Silva-Del-Rio et al. (2017) [68], who calculated a negative correlation of r = −0.37. The IgG concentration in the colostrum decreased with an increasing colostrum yield [68]. Kehoe et al. (2011) [59] also determined a negative but weak correlation of r = −0.16. Furthermore, the regression analysis showed a relationship between the colostrum yield and the IgG concentration ($R^2 = 0.03$; $P < 0.01$) [59].

Scholz et al. (2011) [70] concluded that a first milking quantity of more than 7.2 L negatively affects the Ig concentration. Cows with more than 7.2 L of colostrum at first milking had both the lowest total protein content (35.0–205.0 mg mL^{-1}) and the lowest Ig concentration (14.0–179.0 mg mL^{-1}). Cows with less than 4.5 L of first milk had a total protein content of 38.0–245.0 mg mL^{-1} and an Ig concentration of 20.0–203.0 mg mL^{-1} [70]. Løkke et al. (2016) [62], determined a correlation of 0.70 between the total protein content and the IgG concentration. In a study with Holstein-Friesian cows, an increase in the colostrum volume by 1 L showed a 1.4 mg mL^{-1} lower Ig concentration [71]. Another study found no influence of the milked colostrum quantities on the IgG concentration in the colostrum [5].

The decreasing colostrum Ig concentration depends on water diffusion. When lactation starts, the secretion of lactose into the udder increases, whereas the absolute amount of IgG remains the same. Due to the higher volume, there is more dilution [69,72].

Parity

According to Ganz et al. (2018) [73], the Ig concentration in colostrum is correlated with the number of lactations. Older cows produce colostrum with higher Ig levels; this may be because older cows have been exposed to antigens for a longer time than younger cows. Antibodies transfer from the mother cow's serum to the colostrum. As a result, parity can positively influence the Ig concentration in colostrum [74].

Kehoe et al. (2011) [59] determined a notably increased IgG concentration in the colostrum from cows in lactations one to four. Furthermore, cows in the second lactation produced colostrum with the lowest IgG concentration compared to cows in all other lactations; however, there was no statistically significant difference between the first and second lactation cows [59]. This result can also be attributed to a dilution effect. Older cows have been exposed to various antigens over a longer period [74]. On the one hand, cows in the second lactation have not been exposed to the environment for a substantial period, but on the other hand, they do produce significantly more milk than those in the first lactation [75]. As such, the lower concentration of Ig is more diluted in colostrum from the second lactation, compared to that from the first lactation, which may explain the lowest IgG concentration in colostrum from second lactation cows.

In a study of Norwegian dairy cows, Gulliksen et al. (2008) [76] noted an increase in the IgG concentration as the lactation number increased; this increase was particularly evident between cows in their first or second lactation and cows in their fourth or greater lactation. Figure 3.2 shows the Ig concentrations collected across different studies with respect to the lactation number.

Muller and Ellinger (1981) [78] noted a lower IgA concentration ($P < 0.05$) in colostrum from cows in the first lactation compared to those in the third or fourth lactation. When the total Ig concentrations were compared across lactations, cows in the third and fourth lactations had higher levels than cows in the first lactation [78].

Additionally, the mean IgG concentration is often considerably higher during the third lactation than in the first or second lactation [1,30,53,59,68]. This finding was confirmed by Scholz et al. (2011) [70], who noted that the total protein content of young and two-calf cows was significantly ($P \leq 0.05$) lower than that of higher parity cows. The Ig concentration of young and second calf cows was also lower ($P \leq 0.05$) than that of higher parity cows [70]. Similarly, Phipps et al. (2017) [79] found that cows in the fourth or higher lactation had the highest mean Ig concentration in their colostrum in contrast to lower parity cows. More specifically, 49.3% of cows in the fourth lactation had an IgG concentration greater than 50.0 mg mL^{-1}, whereas only 27.9% of cows in the second lactation reached this level. The authors attributed this result to an increased colostrum volume, compared to other lactations, and a stronger dilution effect. Additionally, Silva-Del-Rio et al. (2017) [68] tested the IgG concentration in the second milking of cows. As previously described, the IgG concentration in the second milking is higher in cows in the fourth or greater lactation, compared to those in the second or third lactation [68]. Similar results were described in a study by Johnsen et al. (2016) [45].

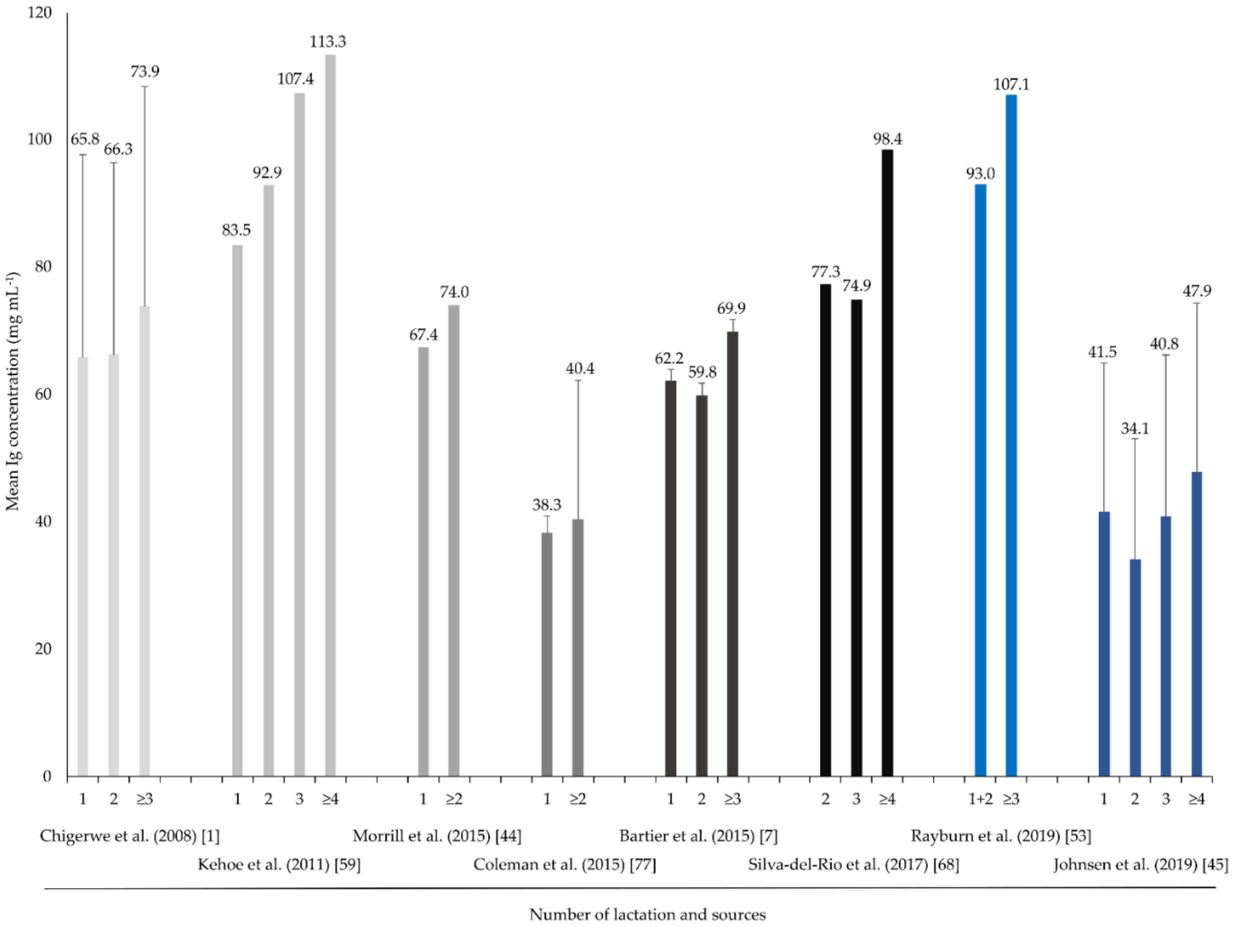

Figure 3.2 Mean Ig concentration (mg mL^{-1}) of cows in different lactations (L = Lactation).

Other studies showed a weak or no correlation between the lactation number and the colostrum Ig concentration [77,80-81]. Cabral et al. (2016) [69] determined a weak correlation (r = 0.22) between the number of lactations and the IgG concentration in the colostrum of Holstein-Friesian cows [69]. Morrill et al. (2015) [44] and Coleman et al. (2015) [77] observed no differences in the colostrum IgG concentration between primiparous and multiparous cows, based on standard methods (RID and TIA). Conversely, Morrill et al. (2015) [44] noted that multiparous cows had a higher IgG concentration than primiparous cows, according to measurements taken with a refractometer and a colostrometer.

In most studies, increases in Ig concentrations are dependent on the number of lactations and do not start until the third lactation. Therefore, it is difficult to make conclusions about animals in the second lactation since they are integrated into the multiparous group. Secondly, biased by milk yield, the effect of lactation alone cannot be evaluated, and colostrum can be classified as good or poor quality by the lactation number alone. Due to the differences between cows in different lactations, colostrum from primiparous cows should only be fed to calves after determining its IgG concentration; it should be replaced by colostrum with a higher Ig concentration if necessary [59,70]. Primiparous cows usually have a low IgG concentration, which can lead to an FPT.

Colostrum with low IgG concentrations can be flagged via measurements, such that colostrum with a higher IgG concentration can be used instead; this has a positive effect on the immune status and, thus, the development of the calf. In this context, different measurement cut-off points should be defined in relation to the number of lactations. According to Bielmann et al. (2010) [20], it is unnecessary to define different cut-off points according to the lactation number when making measurements with a refractometer. A cut-off point of 22.0% Brix can be used for colostrum from first-calf heifers and cows in higher lactations.

Studies have shown that the leakage of colostrum from the udder influences its Ig concentration [82]. In a study by Reschke et al. (2017) [82], colostrum leakage was the most significant ($P < 0.001$) risk factor for the production of colostrum with an insufficient Ig concentration. Regardless of whether the cow loses colostrum prior to or during birth, this loss has a negative effect on its Ig concentration. The IgG-rich colostrum in the udder at the end of the dry period is thus lost [4]. In the case of colostrum being lost through leakage, Ig concentrations shift earlier to transition milk; however, this milk is excreted at the time of the first colostrum. In practice, farmers observed that colostrum leakage appears more frequently in cows with higher lactation numbers, but data on leakage at early lactation are rare. Leakage appears to occur in comparable proportions in multiparous and primiparous cows starting from day nine [83].

Breed and genetic

Comparative studies suggest that there are differences in the Ig concentration in colostrum between different breeds. In 1981, Muller and Ellinger [78] already investigated the Ig concentration in the colostrum of five different cattle breeds. They analyzed colostrum samples from Ayrshire, Brown Swiss, Guernsey, Holstein-Friesian, and Jersey cows using RID. No significant differences could be found in the individual Ig concentration. However, a trend became apparent in that Jersey cows consistently had the highest IgG, IgA, and IgM concentrations in the colostrum. In terms of the total Ig concentration, Jersey and Ayrshire cows had higher values than Holstein-Friesian, Guernsey, or Brown Swiss cows [78]. The mean IgG concentration for Jersey cows in Morrill et al. (2015) [44] was 72.8 mg mL^{-1} and had a range of 12.8 mg mL^{-1} to 154.3 mg mL^{-1}, whereas the values in Silve-Del-Rio et al. (2017) [68] were slightly higher (83.5 mg mL^{-1}, 23.7–172.9 mg mL^{-1}). The mean IgG concentration for Holstein-Friesian cows is similar but mostly lower compared to Jersey cows, with 68.5 [1], 64.7 [11], 65.1 [42], 57.7 [60], and 73.4 mg mL^{-1} [8]. In another study, the IgG concentration in the colostrum of Holstein-Friesian cows, Jersey cows, and a Holstein-Friesian-Jersey cross was determined using a Brix refractometer. For the Holstein-Friesian cows, the %Brix value was 18.9%, for Jersey cows it was 21.3%, and it was 20.1% for the crossbreds.

Consequently, in this study, Jersey cows showed a higher IgG concentration than Holstein-Friesian cows. However, the factor breed failed to be significant (*P* < 0.05) [79]. A study with 2,500 lactating Jersey cows recorded a mean Brix value of 26.6% [84]. These results are not congruent with the outcomes of Coleman et al. (2015) [77], who did not find differences between the concentration of IgG in colostrum from Holstein-Friesian and Jersey cows.

In general, beef cows should have a higher Ig concentration in the colostrum than dairy cows. This opinion is concordant with the studies of Gamsjäger et al. (2020) [54], in which the cut-off points for low-IgG colostrum and high IgG colostrum for 416 colostrum samples from one beef breed deviate strongly from the normally used cut-off point of 50.0 mg IgG mL^{-1}. The cut-off point for low-IgG colostrum was at < 100.0 mg $mL^{-1,}$ and the cut-off point for high-IgG colostrum was at ≥ 150.0 mg mL^{-1}. Although these values are much higher, 49.8% of the samples contained IgG ≥ 150.0 mg $mL^{-1,}$ and only 9.1% were below the cut-off point of 100.0 mg mL^{-1}. However, even in this study, the IgG concentration in the colostrum varied greatly (19.2–264.7 mg mL^{-1}). These variations are also found in studies with dairy breeds [54]. The average IgG concentration measured using RID in a study by Elsohaby et al. (2018) [43], including beef cows, was 143.2 mg mL^{-1}, just below the previously indicated cut-off point of 150.0 mg mL^{-1}. This cut-off point was even exceeded for colostrum samples from Charolais in Martin et al. (2021) [6] (158.4 mg mL^{-1}). In contrast to the IgG concentration in the colostrum of beef cows, an average IgG concentration of 65.5 mg mL^{-1} was found in a study by Elsohaby et al. (2018) [43] for dairy cows. Since it seems that beef breeds have higher Ig concentrations in their colostrum, the cut-off point for these breeds could be set directly higher than for dairy breeds. Considering the calf's intake capacity and need, calves with a low intake should be fed with colostrum containing a high concentration of Ig. In this way, the calf is able to absorb a sufficient amount of Ig despite the low quantity of colostrum provided. Accordingly, the colostrum that exceeded a higher cut-off point could be used at this point.

In their study, Vandeputte et al. (2014) [81] measured the IgG_1 concentration in the colostrum of four beef breeds (Charolais, Belgian Blue, Blonde d'Aquitaine, and Limousine). However, the average IgG_1 concentration did not differ between the four breeds. The mean IgG concentration across all the breeds was 95.9 mg mL^{-1}, which is higher than figures recorded in studies with dairy breeds [81]. Dunn et al. (2018) [35] did not detect any differences between the IgG concentration in the colostrum of ten Holstein-Friesian and ten crossbred animals (Limousine × Holstein-Friesian). In addition, the factor breed did not affect the IgG concentration, neither related to the first nor the fifth milking after birth [35]. However, the sample size is minimal, and the results should be evaluated accordingly.

Figure 3.3 shows varying Ig concentrations of different studies, subdivided by the breeding goal of the used cows. The minimum and maximum Ig concentration, mean Ig concentration, minimum and maximum standard deviation (SD), and the weighted mean of the groups are shown. Specific breeds were ranked within the breed groups by the milk yield (high to low) they produced. It is suspected that the breed-specific differences are due to genetic parameters and dilution effects [15]. In a comparison between Holstein Friesian and Charolais, the concentration of IgG_1 ($P = 0.06$), IgG_2 ($P < 0.01$), IgM ($P < 0.01$), IgA ($P = 0.08$), and total Ig ($P < 0.05$) in colostrum were found to be higher in Charolais. In Holstein-Friesian cows, the total mass (concentration × yield) of IgG_1, IgG_2, IgM, IgA, and total Ig was significantly higher [85]. However, the colostrum yield produced by Holstein-Friesian cows is higher than that produced by Charolais [85]. It can be concluded that there is a greater dilution of Ig and, as a result, a lower concentration of Ig.

Some studies have explored the relationship between genetic aspects and the Ig concentration in colostrum. Karl and Staufenbiel (2017) [71] identified cow sires as an important antepartum influencing factor on the Ig concentration. For the authors, genetics, i.e., the cow sire, even represents the most important influencing factor on Ig concentration. In their opinion, it is, therefore, possible to influence the Ig concentration in the colostrum of the daughters through targeted selection. However, they also pointed out that the bull´s daughters, who inherited the highest Ig concentration, also had the lowest colostrum yield at the first milking.

This outcome indicates the dilution effect already mentioned. In addition, the individual range of the animals must still be considered. Nevertheless, the authors see genetics as a starting point for influencing the colostrum Ig concentration [71].

Conneely et al. (2013) [74] calculated a low heritability of 0.10 for the IgG concentration. The genetic standard deviation for IgG concentration and genetic variation coefficient were 16.0 mg mL^{-1} and 14.3%, respectively [74]. A study by Soufleri et al. (2019) [90] focused on the genetic background of the Ig concentration in colostrum and calculated the heritability for the total protein content and the colostrum total solids. Total solids in colostrum can be calculated indirectly using a refractometer and can be used to estimate the Ig concentration in colostrum. The total protein content had a heritability of 0.19, and total solids had a heritability of 0.27 ($P < 0.05$).

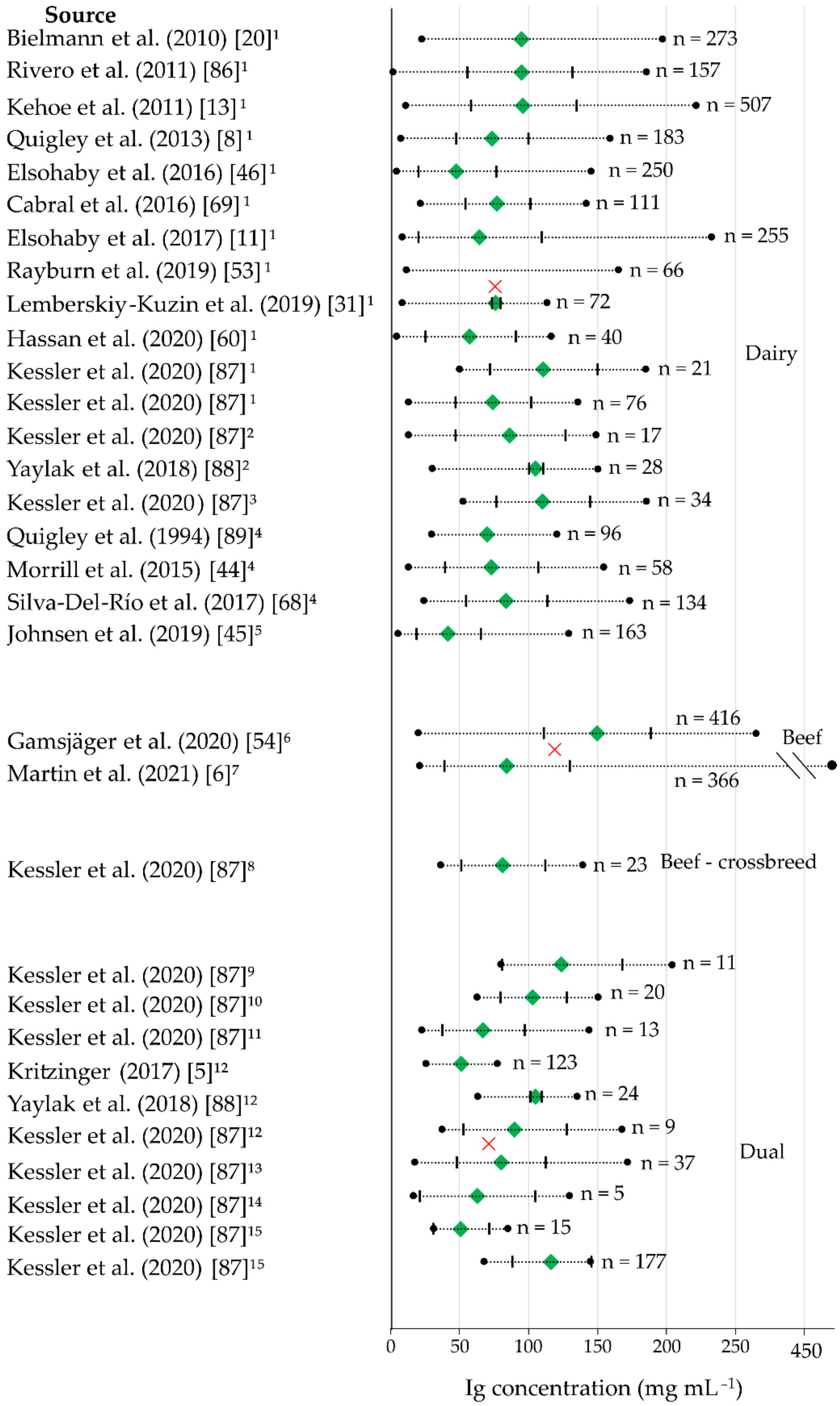

Figure 3.3 Ig concentration (mg mL^{-1}) in colostrum of different breeds sorted by dairy, beef, meat crossbreeds, and dual breeds, (● Minimum and Maximum Ig concentration, ◆ Mean Ig concentration, ▮ Minimum and Maximum SD, × Weighted average of the group. [1]Holstein-Friesian; [2]New Zealand Holstein-Friesian; [3]Brown Swiss; [4]Jersey; [5]Norwegian Red; [6]mixed beef breeds; [7]Charolais; [8]Holstein-Friesian × Charolais; [9]Montbéliarde; [10]Holstein-Friesian × Montbéliarde; [11]Pinzgauer; [12]Simmental; [13]Rhetic Gray; [14]Murnau-Werdenfelds; [15]Original Braunvieh)

Dry Period Length

Scholz et al. (2015) [70] found that the duration of the dry period has an influence on the Ig concentration in the colostrum. In their study, cows with a dry period longer than 62 days had 21.0 mg mL^{-1} more total protein content in their colostrum, compared to cows with a dry period of 46 days. In addition, a longer dry period (46 days) resulted in a 17.0 mg mL^{-1} higher Ig concentration in the colostrum. Furthermore, the total protein content in the colostrum varied considerably with the dry period length and number of lactations. The authors observed an increase in the total protein content of colostrum from second calving cows (from 61.0 mg mL^{-1} to 93.0 mg mL^{-1}) when the dry period increased from 46 to 62 days. However, the influence of the dry period length decreased from the fourth lactation onwards (n = 238) [70]. According to Cabral et al. (2016) [69], the IgG concentration is weakly, but positively, correlated with the dry period length (r = 0.17) and colostrum yield (r = 0.09).

These results were confirmed by Karl and Staufenbiel (2017) [71]. They found a significant correlation (r = 0.14, $P < 0.05$) between the Ig concentration and the dry period length. Extending the dry period by one day led to a 0.05 mg mL^{-1} increase in the Ig concentration, whereas a 10-day extension increased the Ig concentration by 2.2 mg mL^{-1}. The authors stated that the regeneration of the udder during the dry period influences the Ig concentration in the colostrum. However, the authors also consider this influence to be too small in practice, as the dry period's length is not only determined by the expected colostrum Ig concentration. Instead, the length depends on management factors and is a complex procedure [71,91]. Rastani et al. (2005) [92] noted a lower IgG concentration in cows without a planned dry period, compared to cows with a dry period of 28 days (49.8 mg mL^{-1} vs. 77.9 mg mL^{-1}). According to Watters et al. (2007) [93] and Gulay et al. (2005) [94], the IgG transfer into colostrum is not affected by a reduction in the dry period length. In colostrum samples from 781 Holstein-Friesian cows, there was a slight difference in the IgG concentration depending on the dry period length. One group of cows was dry stalled for 55 days, whereas the other group was dry stalled for 34 days; the former group had an IgG concentration of 5,849 mg dL^{-1}, and the latter group had a similar IgG concentration of 5,616 mg dL^{-1} ($P = 0.31$) [93]. Mansfeld et al. (2012) [91] hypothesized that the decline in Ig concentration is due to the dilution effect that occurs if there is no dry period. The dilution effect leads to low IgG levels in the colostrum [91]. Colostrum is formed during the last weeks of gestation, and changes in oestrogen and progesterone concentrations have a decisive influence on the transportation of Ig into the milk. At the beginning of calving, transportation decreases due to rising prolactin levels; IgG transport is eventually terminated [5,95].

A longer dry period also occurs when the pregnancy lasts longer. With a longer gestation, the dry period is also longer; thus, IgG transport into the udder is possible over a longer period, leading to a higher concentration in the colostrum.

3.3.2 Environmental Factors

Time from Calving to Milking and First Feeding Postpartum

Studies indicate that managing the interval from birth to first milking should be considered in terms of securing an adequate colostrum supply, especially on farms where the IgG concentration in colostrum is generally very low [68]. A study of 56 Holstein Friesian cows assessed calving-to-first milking intervals of 0.3 h to 23.8 h, noting a significant negative ($R^2 = 0.18$; $P = 0.001$) relationship between the IgG concentration in colostrum and the interval between calving and first milking. The longer the time interval to the first milking is, the lower the IgG concentration is. In fact, the IgG concentration decreased by 3.7% with every increasing hour [14]. In a study by Kritzinger (2017) [5], the IgG concentration of the colostrum decreased by a factor of 1.7 every hour. The influence of the interval between calving and milking was described as statistically significant ($P = 0.013$) and the calculated correlation coefficient was −0.22 [5]. In agreement with the results of Sutter et al. (2019) [30], both studies described a negative correlation between the interval from calving to colostrum collection. Within a study by Scholz et al. (2011) [70], there was a 41.0% decrease in the Ig concentration in the first 9 h after birth. An additional study showed that the IgG concentration in the colostrum collected 6 h after birth was already lower ($P < 0.05$) than the concentration of the colostrum collected 2 h after birth [96].

A similar trend (i.e., negative correlation between the time to first milking and the IgG concentration) was also found when using a refractometer. When the first milking took place in the first 12 h p.p., the average %Brix value was higher (24.4% Brix) than when the milking took place after more than 12 h (17.5% Brix; $P < 0.05$). More specifically, 68.6% of the samples obtained in the first 12 h were above or equal to 22.0% Brix (≥ 50.0 mg IgG mL^{-1}); of the samples taken after the first 12 h, 16.3% met or exceeded this threshold. Overall, the %Brix value decreased by 25.0% per h p.p. [79].

Elfstrand et al. (2002) [97] investigated the concentration of different Ig (IgG_1, IgG_2, IgA, and IgM) in colostrum collected in the first three to four milkings (from 0 h to 80 h after birth) using RID. The concentration of all four Ig subtypes decreased as the number of milkings increased. IgA had the highest concentration (1.6 mg mL^{-1}) in the first 10 h p.p., which decreased by 50.0% in the next 10 h. IgG_2 decreased by 30.0% in the first 10 h p.p., but then remained unchanged in the following 10 h. The concentration of IgM decreased by half in the first 11 to 20 h p.p.; in the next 10 h, the concentration reduced by an additional 10.0%. The authors concluded that the concentration of individual Ig decreases with each milking; however, this occurs at different rates over the entire period, depending on the Ig subtype [97]. Table 3.5 shows the different concentrations at time points < 6,6–11, and >11 h p.p., in comparison to the concentrations of IgG in the studies by Silva-Del-Rio et al. (2017) [68] and Moore et al. (2005) [96].

Table 3.5 Different concentrations (mg mL^{-1}) of Ig subtypes measured in three studies at different time points postpartum.

Time Interval Postpartum	**IgG** (mg mL^{-1})	**IgG** (mg mL^{-1})	**IgG_1** (mg mL^{-1})	**IgG_2** (mg mL^{-1})	**IgA** (mg mL^{-1})	**IgM** (mg mL^{-1})
< 6 h	96.7	113.0	90.0	2.8	1.6	4.5
6–11 h	82.1	94.0 (6 h) 82.0 (10 h)	79.0	1.9	1.7	4.0
> 11 h	84.1	76.0	65.0	1.8	0.9	2.3
Source	[68]	[96]		[97]		

IgG = Immunoglobulin G; IgM = Immunoglobulin M; IgA = Immunoglobulin A

In a study by Silva-Del-Rio et al. (2017) [68], the average IgG concentration in the first milking (9 h 25 min, SD = 3 h 50 min) was 83.8 mg mL^{-1}, whereas the average in the second milking (21 h, SD = 3 h 40 min) was 46.9 mg IgG mL^{-1} [69]. Rayburn et al. (2019) [53] also measured the IgG concentration in colostrum (first milking after birth) as well as in the second to sixth milking after birth using a cut-off point of > 50.0 mg IgG mL^{-1} as indicative of a sufficient Ig concentration; 95.5% of colostrum samples exceeded the cut-off, and 36.5% of second milking samples were above the cut-off point. For the third milking after birth, the cut-off point was decreased to > 25.0 mg IgG mL^{-1}, and 13.1% of the samples exceeded this value. The cut-off point for the fourth and fifth milking after birth was > 10.0 mg IgG mL^{-1} and 23.7% and 3.8% of the samples, respectively, reached the cut-off point. From the sixth milking onward, all the samples had an IgG concentration of less than 10.0 mg IgG mL^{-1}. The samples from the third milking onward had lower IgG concentrations than those in the colostrum and second milk samples. As such, feeding a calf milk from the third milking after birth and onward would lead to a lower IgG intake and an FPT may occur [53]. However, the third and fourth milkings should still be included in the calf's diet because the intake of IgG over a longer period after birth reduces the incidence of diarrheal diseases [98]. Colostral Ig acts in the blood serum but can still have a local protective function in the digestive tract after intestine closure [99]. As such, the prolonged feeding of colostrum can lead to reduced morbidity in newborn calves and reduced use of antimicrobials on farms [98].

Based on the results of these studies, the early milking of cows after birth is clearly necessary to obtain colostrum with high Ig levels. All the studies show a clear decreasing trend for Ig concentration with increasing distance to calving. Implementing this management practice is the only way to ensure an adequate supply of Ig for the calf [14,70].

The importance of the adequate and timely supply of colostrum is well understood. In a survey of 92 participants in Germany, 95.1% of respondents stated that the fastest possible supply of colostrum is the most important aspect of colostrum management [100]. Additionally, 83.7% of the respondents of an Austrian survey feed the first colostrum to the calf within the first 4 h of life, with 13.5% providing it within 4 h to 6 h after birth; only 1.1% feed the first colostrum later than 6 h after birth. Most respondents feed around 2 L to 4 L of colostrum in the first 6 h of life (71.9%); however, 13.3% of respondents feed less than 2 L. On the other hand, 12.7% of respondents feed more than 4 L to their calves in the first 6 h of life [26]. In another study, 72.5% of respondents (n = 40) reported that the first feeding of colostrum occurs within the first 6 h of life; however, 72.5% feed restrictively, 27.5% feed ad libitum, and 35.0% feed a minimum of 3 L [67]. These studies illustrate that calves should be fed colostrum as soon as possible after birth. The first feeding should take place within the first 2 h after birth [15]. Accordingly, the first milking should also occur within this period, although Godden et al. (2008) [4] noted that a delay of up to 6 h was acceptable.

If the colostrum contains a high concentration of Ig, the volume of colostrum that needs to be fed may be lower than if colostrum has a lower Ig concentration. In the latter case, the calf has to take in more colostrum to absorb the same amount of Ig [52]. In this respect, the maximum voluntary intake of each calf should also be considered; not all calves have the same intake and forced feeding (e.g., via a tube) can have negative consequences for the calf, such as gassing of the rumen. Overfeeding must, therefore, be avoided [101].

Treatment Procedures

To ensure a timely supply of calves with colostrum that has a sufficient Ig concentration, it is recommended that frozen colostrum reserves are kept. These reserves can be used if fresh colostrum is unavailable in time or if the dam's colostrum does not contain enough Ig and an FPT could occur. Before feeding, the frozen colostrum must be thawed and warmed up gently but also quickly. To feed adequate colostrum, freezing, thawing, and heating processes must be known to influence the Ig concentration.

Morrill et al. (2015) [44] investigated the influence of freezing on IgG concentration in colostrum. The IgG concentration in the colostrum was measured using RID, a refractometer, and a colostrometer no later than 2 h after milking, and the colostrum was then frozen at −20°C. After seven days, the colostrum was thawed for the first time and warmed to room temperature. Two further cycles followed. The samples were thawed and warmed again after 14 days and one year and the IgG concentration was measured at the respective time points. If the colostrum was frozen only once, no influence on the concentration was found compared to the measurement 2 h after milking using a refractometer and a colostrometer. After two freezing cycles, a lower IgG concentration was measured using RID in the colostrum. No difference was observed if the cow was primiparous or multiparous. An influence on the results of the refractometer and colostrometer measurements was also excluded. The authors suggested that multiple freezing cycles have a negative impact on the accuracy of the RID [44]. In a study by Bielmann et al. (2010) [20], high correlations were found between the Brix values measured using optical and digital refractometers for fresh and frozen colostrum samples (r = 0.98 and r = 0.97; $P < 0.001$). According to the authors, these results showed that the freezing and steeping of colostrum do not influence the results of the two measuring devices [20]. Furthermore, heating colostrum does not seem to affect the Ig concentration of the results from optical and digital refractometers, regardless of the heating period or temperature [42].

Pfeiffer et al. (2010) [102] tested two different methods for thawing colostrum samples – water bath and microwave. In the water bath, the samples were thawed at 46°C within 60 min and then heated. The microwave thawed the samples at 250 watts for 15 min under temperature control. The IgG concentration was determined for the fresh samples and the warmed samples using RID. Before heating, the mean IgG concentration of the samples was 138.0 mg mL^{-1}. After heating, the mean IgG concentration was 79.0 mg mL^{-1} for the water bath samples and 76.0 mg mL^{-1} for the microwave samples. A loss of 44.0% was observed for both methods. The IgG concentration was, therefore, still above the limit of 50.0 mg IgG mL^{-1}. No significant differences in the IgG concentration could be found between the two methods after thawing, although macroscopically visible coagulation was observed in the heated microwave colostrum. The authors concluded that thawing by microwave at 250 watts for 15 min has no negative effect on the IgG concentration of the thawed colostrum. Thus, this method proves to be a faster way of thawing, as the effort is reduced to 45 min compared to the water basin [102]. However, the authors' conclusion should be considered critical because even when the Ig concentration is above 50.0 mg mL^{-1}, there was a 44.0% loss. Since the Igs are a very valuable component of the colostrum, the loss should be kept as low as possible. The Ig concentration of the colostrum should be as high as possible, and losses should preferably not occur at all or only to a minimal extent. In this context, a reduction of 44.0% is certainly to be considered critical, even if the cut-off point has not yet been undershot. Larger surfaces can also be defrosted more quickly. This aspect could be considered in the freezing process. Furthermore, the vessel in which the colostrum is frozen could influence the thawing process. However, up until this date, studies on this are not available.

Elizondo-Salazar et al. (2010) [103] studied the identification of the ideal time and temperature range for heat treatments of colostrum with the least possible effect on the IgG concentration measured using RID. They found that the total IgG concentration decreases with increased temperature and over the time during which the colostrum was heated. A reduction was observed when the colostrum was heated to 60°C, even if it was only heated for 30 min. The most significant decrease in the IgG concentration occurred at a temperature of 63°C [103]. Elsohaby et al. (2018) [42] came to similar conclusions, where the average IgG concentration measured using RID was 45.6 mg mL^{-1}. When the colostrum was heated at 63°C for 30 min or 63°C for 60 min, the average IgG concentration measured using RID decreased to 31.1 mg mL^{-1} and 30.0 mg mL^{-1}, respectively. The IgG concentration decreased by 27.0% and 29.0% [42]. Hassan et al. (2020) [60] treated colostrum at 60°C for 60 min, at 63.5°C for 30 min, and at 72.0°C for 15 s in a water bath to find out which temperature cut-off point has an influence on viscosity in relation to IgG concentration. For all three temperature-time combinations, they found a change in the viscosity of the samples measured visually and using a viscometer. The authors conclude that heating colostrum (containing an IgG concentration lower than 80.0 mg mL^{-1} and 68.0 mg mL^{-1}) at 60°C for 60 min and at 63.5°C for 30 min has no significant effect on the viscosity or the IgG concentration independent of the measurement method [60]. An older study investigated a gentler heating process in which the colostrum was first heated to 60°C for 30 min and held at this temperature for a further 120 min. After that, the colostrum was cooled down to 38°C within 15 min. No difference in the IgG concentrations measured using a TIA was found between the fresh colostrum and the colostrum heated at 60°C for 120 min. The reduction in IgG concentration was 2.2% [104].

Heating causes denaturation of the proteins, which results in their loss of regular activity [105,106]. The measuring methods that provide information on the Ig concentration via density (e.g., colostrometer and refractometer) cannot distinguish between intact and denatured Ig. Only specific methods (e.g., ELISA and RID) can do this. Therefore, if the effects of heating and freezing on the Ig concentration in colostrum are to be investigated, specific methods should be used for determination.

3.3.3 Other Possible Influencial Factors

Gross et al. (2017) [32] investigated the Ig concentration in colostrum at quarter-milking levels, in comparison with the Ig concentration of composite colostrum. There was no association between the colostrum quantity and the IgG concentration, whether at the quarter-milk level or within the composite colostrum. In their study, the concentration and total IgG mass in composite colostrum were higher in multiparous than in primiparous cows ($P < 0.05$), but there were no differences between primiparous and multiparous cows at the quarter-milking level. The range in values for IgG concentrations at the quarter-milking level was similar for primiparous and multiparous cows. In contrast, the IgG mass at the quarter-milk level was lower for primiparous cows than for multiparous cows [32].

In terms of somatic cell counts (SCC), cows with an SCC > 50,000 cells mL^{-1} have lower IgG concentrations (< 30.0 mg mL^{-1}) after calving than cows with a lower SCC. There is no correlation between the SCC of the previous lactation and the IgG concentration [76]. Kehoe et al. (2007) [13] recorded higher IgG_2 concentrations for cows on farms with a herd average SCC < 200,000 cells mL^{-1} in the month prior to sample collection. Overall, the colostrum had a qualitatively higher nutrient composition at lower SCCs. These results contradict those of Cabral et al. (2016) [69], who did not detect any influence of SCC on the IgG concentration in colostrum. The SCC of the previous lactation has no effect on the IgG concentration; however, mastitis during the dry period can affect the IgG concentration in colostrum [69]. Furthermore, there was no correlation between common diseases (e.g., milk fever, prolonged pregnancy, retained placenta, dystocia, and mastitis) and the IgG concentration in colostrum [76].

The calving season may also influence Ig concentration. Gulliksen et al. (2008) [76] noted a significantly (CI: 95.0%) lower IgG concentration in the colostrum from cows that calved in the winter, compared to other seasons. More specifically, cows calving in August, September, or October produced colostrum with higher IgG concentrations than cows calving in the other months. The authors assumed this was due to the advantage of the pasture, which is legally prescribed in Norway [76]; however, in a study by Pritchett et al. (1991) [107], there was no significant effect of season on the IgG_1 concentration in colostrum. Farmers also suggest changing the stable environment to enhance immune responses and possibly the active Ig content, but there is no scientific evidence to support this strategy. In different seasons, there can be strong temperature fluctuations. According to Cabral et al. (2016) [69], heat stress has a negative effect on IgG concentration; they found a negative correlation between the number of days above 23°C during the last 21 days before birth and the IgG concentration in the colostrum. An Italian study confirmed this negative correlation, wherein the concentration of IgG and IgA decreased under heat stress [108]. Conneely et al. (2013) [74] also found that cows calving in April produced colostrum with a lower IgG concentration than cows that calved in the early spring or fall. These studies illustrate the potential influence of environmental temperature on the IgG concentration in colostrum. This factor should be taken into account in future studies.

Blecha et al. (1981) [109] studied the effect of dietary protein restriction during the 100 days before birth on the Ig concentration in colostrum; they found no significant correlation between the concentrations of IgM, IgG_1, and IgG_2 in the colostrum and daily protein intake in the 100 days before birth. Additionally, different energy concentrations in the feed during the dry period (56 to 8 days before birth) did not influence the total Ig concentration, nor the concentration of IgG or IgM. However, the colostrum from cows in the “high energy” group had significantly ($P < 0.01$) higher concentrations of IgA compared to that from cows in the "low energy" group [110]. Similarly, Mann et al. (2016) [111] investigated the effect of different dry period feeding management practices on the IgG concentration in colostrum. Cows fed a restricted energy diet during the dry period showed a higher IgG concentration, whereas cows fed a higher energy density diet produced colostrum with lower IgG concentrations. As such, under some conditions, energy deficiency may impair the Ig concentration.

3.4 Conclusions

On dairy farms, calf rearing and its associated management processes are of particular importance since healthy calves are the basis for the (further) development of the farm. In addition, calf rearing is also receiving increasing public attention. Many studies have investigated the various aspects of colostrum management, the factors that influence Ig concentration, and Ig concentration measurement techniques. Studies have shown that colostrum management, in particular, is a decisive factor in calves' health maintenance and survival, and thus forms the basis for their well-being. A high Ig concentration in the colostrum is a key component for successful colostrum management. This review has summarized, compared, and discussed the most important results in this research area. Thus, it contributes to a transparent presentation of significant findings and identifying the remaining problems in this context.

Different methods permit the estimation of Ig concentrations. Direct methods, such as RID and ELISA, represent the gold standard. TIA and IR spectroscopy are other laboratory methods. Nonetheless, the direct methods described in this review are not practical for use on farms; they are time-consuming, and the results are not available within 3 h. Moreover, since these are laboratory methods, specific procedures must be followed, and their performance is not intuitive. Furthermore, these methods require special reagents that would have to be ordered. The application of the methods would also have to be shown to the farmers by trained personnel. In addition, initial supervision would be necessary to ensure proper execution and meaningful results – all in all, they are very time-consuming and labor-intensive methods. The user must have a high level of qualification for using these direct measurement methods.

Nevertheless, with respect to the significance of their results, direct measurement methods are better than indirect methods. It may be possible to develop practical variants of direct laboratory measurement methods for on-farm use. Currently, only indirect methods, such as measurements using a refractometer and a colostrometer can be used on farms. Results for both methods have shown high correlations compared to RID. The refractometer is easier to handle than direct methods and even easier to use than the colostrometer; it is a quick and safe method to measure Ig concentrations. Deriving the Ig concentration from the colostrum's color or weight has been used for years, but is the least accurate method, primarily because it is based solely on visual perception.

Setting a cut-off value (< 50.0 mg mL^{-1}) reduces the amount of information that is obtained. If the colostrum intake of the calf is below the targeted 10.0–12.0% of the calf’s body mass, higher IgG concentrations are desirable to avoid an FPT. However, if only the commonly used threshold of 50.0 mg mL^{-1} is applied, information on the actual concentration is missing. There is much potential for improvement in the indirect measurement methods. To date, it is impossible to automatically measure the Ig concentration of colostrum and transfer the results directly into, for example, herd management practices. These data could be used to evaluate individual milkings and identify the potential causes of diseases or long-term monitoring. Linking colostrum data with other health data of the calf or cow is also not feasible. As there is currently no possibility to store and process colostrum data automatically, its use in quality management has yet to be established. Digitally recording data would enable farmers to use it without much effort, thus optimizing their calf husbandry. The technical possibilities in this area have not yet been exhausted. For example, new methods already use QR codes and transmit the results to the farmer's smartphone via an application.

The Ig concentration of colostrum is influenced by various factors, which can be categorized as animal- or environment-related factors. A high colostrum yield with a simultaneously low Ig concentration can lead to a strong dilution effect in the colostrum. For each additional liter of colostrum, there is a decrease in the Ig concentration. The number of lactations also influences the Ig concentration. The literature shows that the Ig concentration increases with the lactation number, particularly from the third lactation onward. Therefore, a division into primiparous and multiparous cows is not advantageous with respect to the Ig concentration.

In terms of influential factors, the number of lactations and breed should be considered when feeding colostrum, but no valuable colostrum should be discarded without control. Genetic effects in relation to the colostrum Ig concentration have only scarcely been studied but could play a role in the future. Furthermore, rapid milking and feeding after birth are essential, as the Ig concentration in the colostrum decreases and, at the same time, the calf’s absorption capacity for Ig declines. The first milking and feeding should take place within the first 2 h of life. To feed the calves colostrum containing high Ig concentrations as quickly as possible, even if the mother cow does not ensure such colostrum, frozen reserves of good colostrum are used to replace insufficient colostrum. Due to a gentle thawing process, the Ig concentration of previously frozen colostrum remains almost unchanged. Heating the frozen sample to 60°C within 30 min and maintaining this temperature for another 120 min appears to be the safest option, as numerous studies have shown that this leads to the lowest loss of IgG; however, it does involve an increased time requirement, which can be reduced to 15 min when heating by microwave, although this leads to a 44% loss.

Colostrum management practices have developed considerably in recent years and are becoming an increased focus with respect to improving calf husbandry and health. This development will continue to progress in the coming years, and further developed methods and more detailed studies of the influencing factors will further optimize the opportunities for farmers' colostrum management practices.

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4 Study 2

Survey on colostrum management by German dairy farmers focusing on frozen colostrum storage

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Interpretive Summary

Although successful calf rearing depends on good colostrum management, procedures on German farms are not well characterized. To identify potential for improvements, a survey was conducted to gain insight into colostrum management on German dairy farms. Most farmers understand the necessity of proper colostrum management; however, due to a generally high workload and a lack of clearly defined standard operating procedures, key tasks such as checking colostrum quality and freezing colostrum reserves are performed only occasionally, and the quality of practice is poor. The current information gaps, the need for knowledge transfer, and existing practices should be defined and recorded.

Abstract

Because calves are born with low levels of antibodies, effective colostrum management is one of the most critical factors for successful calf rearing. A timely and adequate supply of sufficiently high-quality colostrum immediately after birth is essential to ensure the passive immunization of calves. Frozen colostrum reserves are recommended to fulfill the immunological and nutrient requirements of newborn calves, even in exceptional situations; however, the implementation rates on German dairy farms and challenges of realization remain unclear. A 33-question online survey, focused on frozen colostrum reserves, was developed to obtain an overview of colostrum management practices on German dairy farms. The questionnaire was divided into three sections: 1. personal data; 2. farm characteristics; 3. colostrum management. Of the 155 responses we received, 63.9% were from female farmers, and 35.5% were from male farmers. Conventional farming was practiced on 89.0% of farms, and organic farming was practiced on 7.1% of farms. Of the respondents, 89.0% froze colostrum. The main reasons for freezing colostrum were: 1. the dam does not produce enough colostrum; 2. the dam cannot be milked; or 3. in cases where the dam dies during birth. Farmers primarily froze colostrum from cows during their third to fifth lactation. Before freezing, 33.1% of the respondents measured indicators in the colostrum to estimate Ig concentrations, whereas 2.3% determined the colostrum quality after freezing. Reusable and disposable PET deposits (23.1%, 22.3%) and ColostroBags (20.0%) were the primary containers used to freeze colostrum. The main reasons for not freezing colostrum were the high labor intensity and the availability of fresh colostrum from other cows. Thawing methods included buckets (47.7%) and professional water baths (13.8%). The survey identified areas in which improved knowledge transfer could enhance colostrum management. Furthermore, there appeared to be a lack of specific, feasible instructions for employees concerning the practical implementation of colostrum management. Most importantly, the regular determination and documentation of Ig concentrations should be emphasized. The added value of stored colostrum, relative to a greater workload, should also be promoted, particularly on smaller farms.

Keywords: colostral immunoglobulin supply, early nutrition, healthy calf rearing, postnatal feeding

Abbreviations: FCR = Frozen colostrum reserves***;*** NOR = No reserves

4.1 Introduction

The practices underlying the health and development of newborn calves are prerequisites for a successful farm operation. Numerous factors influence calf management and, thus, the health and development of the offspring (Murray et al., 2016). In recent years, many of these influencing factors have been intensively described, including housing and birth conditions, feeding management, and colostrum intake (Steinhoff-Wagner et al., 2011a; Klein-Jöbstl et al., 2014). Colostrum has particular importance as the first and most important nutritional and functional source for calves (Furman-Fratczak et al., 2011) because calves are born with a minimal antibody level and limited endogenous energy storage (Blum and Hammon, 2000; Steinhoff-Wagner et al., 2011a). Passive immunization depends on the timely and sufficient intake of good-quality colostrum (Chigerwe et al., 2008; Godden et al., 2019). The amount of colostrum at the first feeding postpartum (p.p.) should be at least 10.0% of the calf's body weight (Godden et al., 2019). Without a colostrum intake with an Ig concentration of ≥ 50.0 mg mL^{-1} in the first 4 h of life, the risk of disease, morbidity, and mortality in calves increases (Tautenhahn, 2017; Urie et al., 2018). High-quality colostrum management can positively influence calves' health status (Furman-Fratczak et al., 2011) and metabolic development (Steinhoff-Wagner et al., 2011). Good colostrum management includes not only feeding sufficient colostrum with enough IgG from the dam but also the timely feeding of colostrum if a shortage occurs. For these cases, establishing colostrum reserves is recommended. These reserves can be stored in a freezer, refrigerator, or at room temperature (Cummins et al., 2017) for some time, depending on the method used. Overall, freezing colostrum is the most practical and effective way to ensure the availability of an adequate colostrum supply for newborn calves at all times; moreover, it carries the lowest risk of microbial contamination and the longest shelf life (Godden et al., 2019). If the dam cannot supply an appropriate quality or quantity of colostrum, the frozen colostrum reserve can be used as a complete replacement or supplement to limited maternal amounts of colostrum for the newborn calf. This situation may occur when the dam dies at birth or the teat canal drips heavily before birth (Cummins et al., 2017; Robbers et al., 2021b). In addition, the dam's colostrum should be replaced if it does not reach the required quality limits, specifically ≥ 50.0 mg Ig mL^{-1} or 22.0% Brix (Ahmann et al., 2021). However, in this scenario, it is important to check the stored colostrum for IgG concentration to ensure higher-quality colostrum because freezing may reduce the viability of functional cells relative to the fresh colostrum (Novo et al., 2017a; Novo et al., 2017b).

Nevertheless, there is a lack of data describing colostrum management practices on German dairy farms, especially regarding colostrum storage. This study aimed to provide (1) an overview of colostrum management in German calf husbandry with a special focus on freezing colostrum reserves and (2) to uncover the challenges faced when implementing this practice by comparing farms that freeze colostrum reserves with those that do not.

4.2 Materials and Methods

4.2.1 Study Sample and Survey Design

To accomplish the objectives of this study, a survey was created using the licensed online survey tool "UNIPARK" (Tivian XI GmbH, Cologne, Germany). The questionnaire was checked for wording, plausibility, comprehensibility, and quality through internal pre-tests with researchers and known farmers (n = 5) and was revised following their feedback. After numerous test runs, the survey link was shared with German dairy farmers via personal e-mails, newsletters, student clubs, magazines, national dairy societies and social media between March and May 2022.

The introductory section of the survey clarified that it was designed to examine dairy farmers' opinions and experiences, independently of whether or not they stored colostrum. The survey was conducted in German, making German-speaking farmers eligible to participate. For clarity, the questionnaire has now been provided in English. In total, the questionnaire contained 33 questions and was divided into three sections: (1) personal information; (2) farm information; and (3) colostrum management. In Section 3, a filter question was used to separate the participants into two groups based on the implementation of frozen colostrum reserves: those who already used frozen colostrum reserves (FCR) and those who lacked practical experience in freezing colostrum (NOR; no reserves). Subsequently, FCR farmers were asked eleven questions, and NOR farmers were asked seven questions about colostrum management. The total number of questions per group was, therefore, different: 26 in FCR and 22 in NOR. In the last branch of the NOR group, the questions were posed hypothetically, each with answer choices identical to those of the FCR group. Figure 4.1 shows the structure of the questionnaire. Different types of questions were used: single choice (n = 14); multiple-choice (n = 10) with preset answers or pictures; partly semiopen questions (additions of other answers possible); some free text field entries (n = 8); and a ranking question (n = 1).

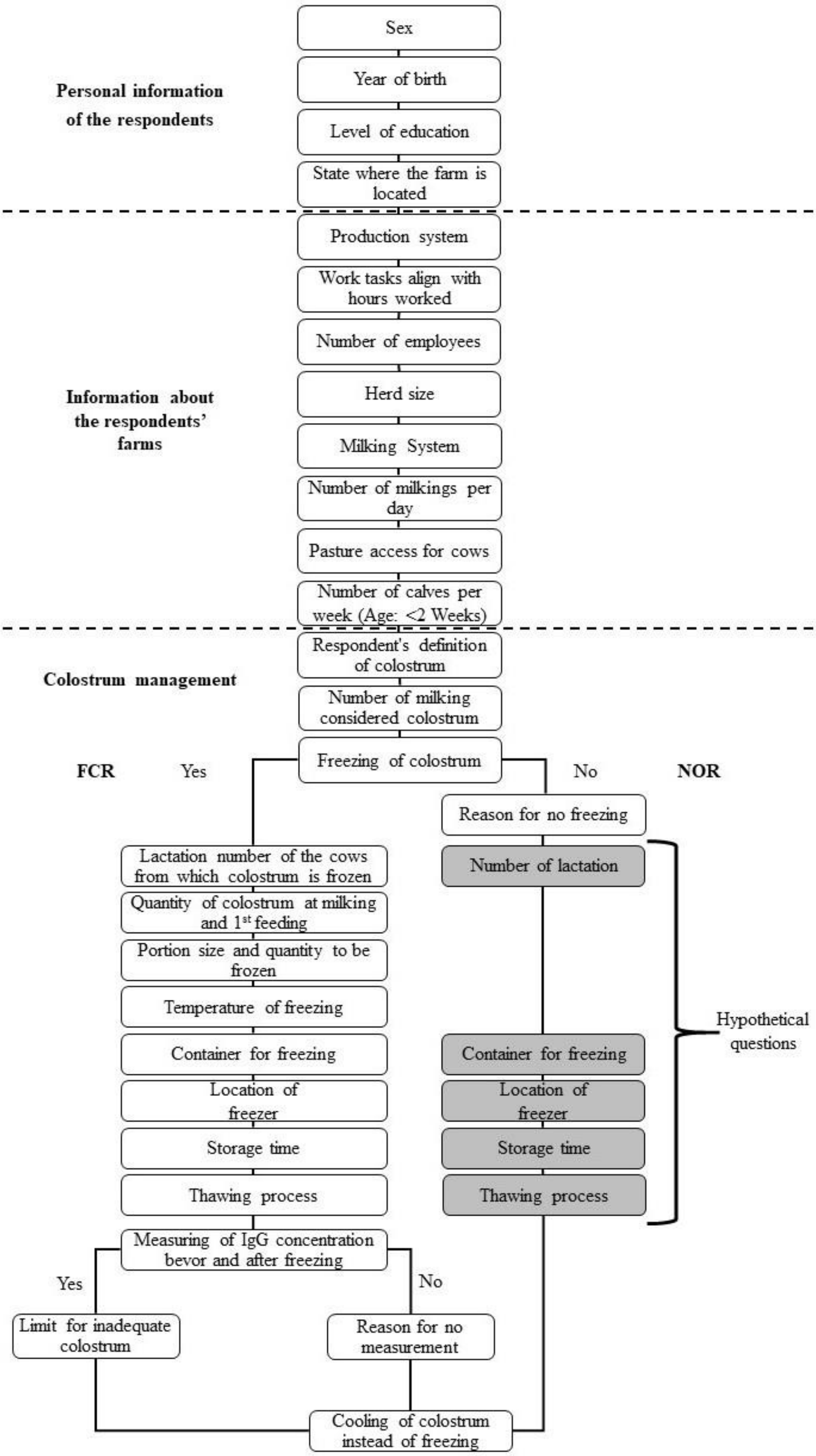

Figure 4.1 Representation of the survey structure (IgG = immunoglobulin G) and the intended comparison between farmers with frozen colostrum reserves (FCR) and those who refrain from having reserves (NOR).

The participants were asked how frequently they performed each task in relation to their total working time on the farm. For a more accurate overview, we assigned all activities to nine different tasks: TASK_STABLE = stable work; TASK_TECH = machine guidance and technical maintenance; TASK_MILK = milking cows; TASK_TREATCALF = treatment of calves; TASK_FEEDCALF = feeding of calves; TASK_TREATCOW = treatment of cows; TASK_FEEDCOW = feeding of cows; TASK_DOC = office work and documentation; TASK_LEAD = operations, management, and investment. Participants rated their working time per task using six different frequencies (typical Likert scale plus an option to refuse a response). A frequency of 1 was used to represent “do not know”, 2 for “never”, 3 for “rarely”, 4 for “occasionally”, 5 for “frequently”, and 6 for “very often”. For more specific evaluation, we classified three subgroups from the tasks mentioned above based on the six frequencies: Subgroup 1 contained survey respondents who scored ≥ 45 points when summing all tasks; Subgroup 2 contained survey respondents who scored 10–12 points when summing the points for TASK_FEEDCALF and TASK_TREATCALF; and Subgroup 3 included survey respondents who scored < 10 points when summing the points for TASK_FEEDCALF and TASK_TREATCALF.

4.2.2 Data Analysis

The survey data were downloaded in spreadsheet format (Excel, Microsoft Corp., Redmont, WA). Further evaluation was performed using Excel and IBM SPSS Statistics Version 29 (IBM Corp., Armonk, NY).

In total, 159 farmers completed the survey. All responses were evaluated and screened for completeness. Text field entries were clustered and numerically coded. Participants remained in the evaluation as long as they answered the filter question during the initial section of the survey. Four individuals did not answer any questions and were removed from the dataset. Therefore, responses from 155 participants were available for analysis. Participants were maintained for examining group-related questions if they responded to at least one question within the associated group block to maximize the number of answers per question. Eight individuals who reported freezing colostrum did not answer any questions. Therefore, these individuals were excluded from further evaluation in the FCR group. One participant in the NOR group did not answer any questions and was removed from further evaluation.

4.2.3 Statistical Analysis

The statistical analysis was performed using IBM SPSS Statistics Version 29 (IBM Corp., Armonk, NY). Data were often ordinal and not normally distributed, as assessed by the Shapiro–Wilk test; therefore, Spearman rank correlations were calculated. Correlation coefficients of |R| > 0.10, |R| > 0.30, and |R| > 0.50 were considered as low, moderate, and high, respectively (Cohen, 1988). P-values of < 0.05, < 0.01, and < 0.001 were considered significant, very significant, and highly significant, respectively. A tendency was considered at 0.05 < P < 0.1. A Mann–Whitney U test was performed to evaluate differences in respondents and farm characteristics between the two groups (FCR vs. NOR) and the option of measuring the IgG concentration in colostrum before freezing it.

4.3 Results

4.3.1 Characteristics of the Survey Respondents

The participants' personal data and farm information are presented in Table 4.1. The median age of the participants was 32 years (Q1 = 25 years, Q3 = 44 years); the most common age range was 20 years and 29 years old (40.6%), approximately 20.0% of respondents were between 30 years and 39 years old, and only a small percentage was 19 years or younger (2.0%) or 60 years and older (3.9%). Most respondents had obtained a university degree, followed by an apprenticeship in agriculture and a foreman degree. The majority of participants were from farms in North Rhine-Westphalia, Bavaria, and Lower Saxony.

4.3.2 Characteristics of the Farms

Most respondents managed their farms conventionally. The median herd size was 100 lactating cows (Q1 = 60 cows, Q3 = 180 cows) (Table 4.1). The majority of participants (n = 139) had either up to two (28.8%) or three (31.7%) workers, based on full-time employees and a working week of 40 h. Three participants stated zero workers and six responses exceeded the reasonable numbers, indicating that these participants misunderstood the instruction to give values as full-time equivalents or had bigger operations than only the dairy branch. The median number of full-time workers per 100 cows was 2.3. When farms were classified according to herd size, the median number of employees per 100 cows was 4.6 (0.0–125.0) for very small farms (up to 49 cows), 3.1 (0.9–21.4) for small farms (50 to 99 cows), 2.1 (0.0–3.6) for medium farms (100 to 199 cows). The median employee score per 100 cows for large farms (200 to 499 cows) was 1.6 (1.0–3.3) and 1.0 (0.9–1.4) for very large farms (≥ 500 cows).

Table 4.1 Overview of personal data of survey participants and farm information in comparison with German farms in general (n = 155).

Variable	Category	Respondents, (%)	(n)	German distribution, (%)
Sex	Male	35.5	(55)	64.0[1]
	Female	63.9	(99)	36.0[1]
	Diverse	0.0	(0)	na
	No data	0.6	(1)	na
Age [years]	≥ 60	3.9	(6)	na
	59–50	14.8	(23)	na
	49–40	16.1	(25)	na
	39–30	20.6	(32)	na
	29–20	40.6	(63)	na
	< 20	2.0	(3)	na
	No data	2.0	(3)	na
Highest level of education	Secondary school or no degree	0.0	(0)	na
	Highschool degree	10.3	(16)	na
	College	11.6	(18)	na
	Graduated in Agriculture	5.1	(8)	15.2[2]
	Apprenticeship	24.5	(38)	27.9[2]
	Agricultural	20.0	(31)	na
	Different	4.5	(7)	na
	Foreman degree	19.4	(30)	21.9[2]
	University of applied sciences and arts	4.5	(7)	na
	University degree	24.5	(38)	13.9[2]
German state	North Rhine-Westphalia	24.5	(38)	12.8[3]
	Bavaria	20.6	(32)	32,3[3]
	Lower Saxony	15.5	(24)	13.5[3]
	Hessen	8.4	(13)	5.8[3]
	Baden-Württemberg	7.7	(12)	14,9[3]
	Schleswig Holstein	6.5	(10)	4.6[3]
	Rhineland Palatinate	3.9	(6)	6.1[3]
	Saxony	1.9	(3)	2.5[3]
	Brandenburg	1.3	(2)	2.1[3]
	Saarland	0.6	(1)	0.4[3]
	Saxony-Anhalt	0.6	(1)	1.7[3]
	Mecklenburg Western Pomerania	0.6	(1)	1.8[3]
	Thuringia	0.6	(1)	1.4[3]
	City States	0.6	(1)	1.4[3]
	Different country	4.5	(7)	na
	No data	1.9	(3)	na
Production system	Conventional	89.0	(138)	90.1[3]
	Ecological	7.1	(11)	9.9[3]
	Different	0.6	(1)	na
	No data	3.2	(5)	na
Herd size [number of lactating cows]	< 10	1.3	(2)	9.6[4]
	10–19	0.6	(1)	12.0[4]
	20–49	15.5	(24)	30.6[4]
	50–99	29.7	(46)	28.2[4]
	100–199	26.5	(41)	14.3[4]
	200–499	16.8	(26)	4.2[4]
	≥ 500	5.2	(8)	2.0[4]
	No data	4.5	(7)	na

[1]Source: Federal and state statistical offices (2021); [2]Source: Federal Statistical Office of Germany (2021a); [3]Source: Federal Statistical Office of Germany (2021b); [4]Federal Ministry of Food and Agriculture (2021); [5]na = not available

Figure 4.2 illustrates that the participants' workload is very high, showing that all nine tasks are performed very often or frequently. It is also evident that participants who focused on the calf-related tasks (TASK_TREATCALF and TASK_FEEDCALF) worked less frequently on other tasks. A highly significant correlation (r = 0.69, $P < 0.001$) was observed between TASK_FEEDCALF and TASK_TREATCALF (Table 4.2). Participants who rated their work time in calf management (TASK_TREATCALF and TASK_FEEDCALF) or livestock-related tasks (TASK_MILK, TASK_TREATCOW, TASK_FEEDCOW) as frequent or very often froze colostrum more often than those who rated their efforts as never or rare.

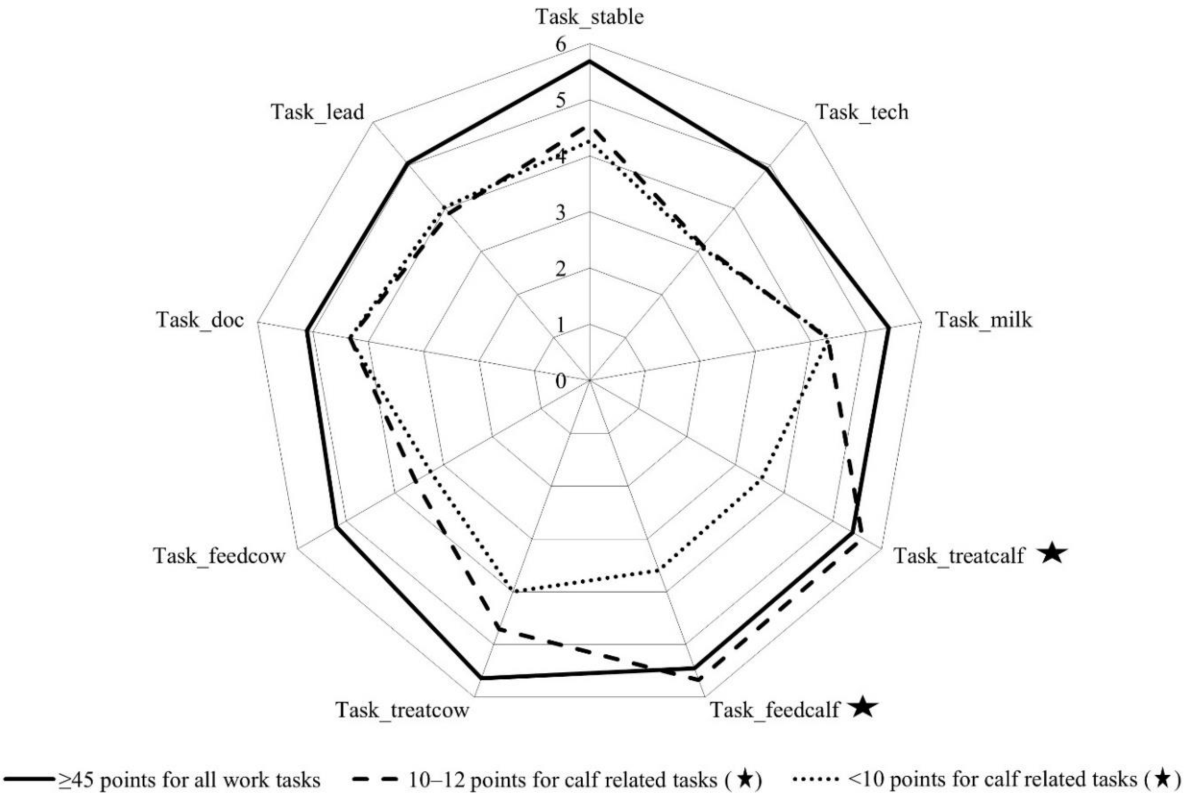

Figure 4.2 Differences in the distribution of various tasks in relation to total work time based on an assessment of the nine tasks using the Likert Scale (1 = don´t know, 2 = never, 3 = rare, 4 = occasionally, 5 = frequent, 6 = very often).

Furthermore, the testing of IgG concentration before freezing was more frequently conducted when participants reported performing calving or animal husbandry work tasks frequently or very often. In the subgroup with a much smaller focus on TASK_TREATCALF and TASK_FEEDCALF, the management-related tasks TASK_LEAD and TASK_DOC are emphasized, and a highly significant correlation (r = 0.57, $P < 0.001$) was also observed between these two tasks. TASK_TREATCALF and TASK_TREATCOW had another moderately significant correlation (r = 0.47, $P < 0.001$). Subgroup 1 had smaller herd sizes compared to Subgroup 2 ($P = 0.02$); however, none of the other relevant colostrum management parameters differed between the subgroups. Table 4.3 shows the distribution of the respondents relating to the

Table 4.2 Spearman rank correlation coefficients among the respective tasks related to working time, which is overrated by a 5-point Likert scale representing frequency (n = 155).

Task	**TASK_ STABLE**	**TASK_ TECH**	**TASK_ MILK**	**TASK_TREAT CALF**	**TASK_FEED CALF**	**TASK_TREAT COW**	**TASK_FEED COW**	**TASK_ DOC**	**TASK_ LEAD**
TASK_STABLE	1.00								
TASK_TECH	0.44***	1.00							
TASK_MILK	0.34***	0.17*	1.00						
TASK_TREATCALF	0.23**		-	1.00					
TASK_FEEDCALF	0.24**		-	0.69***	1.00				
TASK_TREATCOW	0.42***	0.37***	0.22**	0.47***	0.23**	1.00			
TASK_FEEDCOW	0.47***	0.56***	-	-	-	0.34**	1.00		
TASK_DOC	-	-	-	0.19*	-	0.25**	-	1.00	
TASK_LEAD	-	0.26**	-	0.16†	-	0.34***	0.16*	0.57***	1.00

TASK_STABLE = stable work; TASK_TECH = machine guidance and technical maintenance; TASK_MILK = milking cows; TASK_TREATCALF = treatment of calves; TASK_FEEDCALF = feeding of calves; TASK_TREATCOW = treatment of cows; TASK_FEEDCOW = feeding of cows; TASK_DOC = office work and documentation; TASK_LEAD = operations, management and investment; *** $P < 0.001$; ** $P < 0.01$; *$P < 0.05$; † $P < 0.1$

farms. In the study population, most participants had a minimum of 0–5 calves under 2 weeks of age to care for simultaneously. Regarding the maximum number of calves under 2 weeks of age, nearly half of the respondents had 1–10 calves. Approximately one-third of the participants used a herringbone milking parlor. On 25.2% of the farms, cows were milked using an automatic milking system (AMS); 71.0% milked the cows twice daily, and 16.8% milked them three times.

Table 4.3 Overview of general farm characteristics (n = 155).

Variable	**Category**	**Respondents,** (%)	(n)
Minimum number of calves under 2 weeks of age to care for per week	0–5	78.7	(122)
	6–10	6.5	(10)
	11–15	3.2	(5)
	16–20	1.9	(3)
	21–25	1.3	(2)
	26–30	1.3	(2)
	> 30	0.6	(1)
	No data	6.5	(10)
Maximum number of calves under 2 weeks of age to care for per week	1–10	51.0	(79)
	11–20	25.8	(40)
	21–30	8.4	(13)
	31–40	2.6	(4)
	41–50	1.9	(3)
	51–60	1.3	(2)
	61–70	0.6	(1)
	> 70	1.3	(2)
	No data	7.1	(11)
Milking System	Herringbone	32.9	(51)
	AMS	25.2	(39)
	Rotary Milker	8.4	(13)
	Tandem	8.4	(13)
	Swing Over	6.5	(10)
	Side by Side	5.8	(9)
	Other	8.3	(13)
	No data	4.5	(7)
Milking frequency per day	1 per day	1.3	(2)
	2 per day	71.0	(110)
	> 2 but < 3	6.5	(10)
	3 per day	16.8	(26)
	> 3 per day	0.6	(1)
	No data	3.8	(6)

AMS = Automated milking system

4.3.3 Colostrum Management

The first milking p.p. was identified as colostrum by 33.5% of all the respondents (Table 4.4), another 18.1% considered the milk up to the second or third milking p.p. to be colostrum, and 2.6% of participants claimed that the tenth milking p.p. was colostrum. Overall, 83.9% of all the participants (n = 155) stated to freeze colostrum. They reported that colostrum was primarily frozen if the dam produces insufficient colostrum, refuses to be milked, or dies after birth.

Table 4.4 Descriptive Overview of Responses Regarding General Colostrum Management.

Variable	Category	Respondents, (n)	Proportion, (%)
Respondent´s definition of colostrum according to the number of milkings after birth (n = 155)	1	52	33.5
	2	28	18.1
	3	28	18.1
	4	12	7.7
	5	8	5.2
	6	4	2.6
	7	2	1.3
	8	5	3.2
	9	0	0.0
	10	4	2.6
	11	1	0.6
	No data	11	7.1
Freezing of colostrum (n = 155)	Yes	130	83.9
	No	17	11.0
	No data	8	5.1
Reason for freezing (n = 130)[1]	To little colostrum produced		
	Yes	115	88.5
	No	15	11.5
	Cow refuses to be milked		
	Yes	86	66.2
	No	44	33.8
	Cow died after birth		
	Yes	84	64.6
	No	45	35.5
	Calf too weak to drink		
	Yes	29	22.3
	No	101	77.7
	Mother abandons the calf		
	Yes	28	21.5
	No	102	75.5
	Calf born at night		
	Yes	22	16.9
	No	108	83.1

[1]Multiple answers possible

The calf's birth time (day vs. night) and inability to drink played a minor role in freezing colostrum. Nevertheless, in open responses, the time frame in relation to feeding outside the regular milking time was frequently mentioned as a reason for freezing, although this was not related to the time of day. Therefore, using the reserves should allow for direct feeding after birth, even if the regular milking time has not yet started. Time and work-related reasons were more important to participants than replacing low-quality colostrum with high-quality colostrum, as indicated by a higher Ig concentration.

4.3.4 Colostrum Management by Respondents who Froze Colostrum

Most of the 130 participants who reported storing frozen colostrum used colostrum from cows in their third to fifth lactation (Table 4.5). Colostrum from second-lactation cows was stored by 43.1% of participants, whereas colostrum from first-lactation cows was frozen by 20.8% of participants. Furthermore, additional criteria for freezing were requested. In addition to parity, 17.7% considered the quality of the colostrum. Although 6.9% of participants did not specify a limit and 66.2% did not respond to this question, 26.9% indicated that they set a threshold for poor colostrum. A limit value in %Brix was stated in 20.0% of the responses: 12.3% set a limit of ≥ 22.0% Brix, and 7.7% used a threshold of < 22.0% Brix. The lowest limit was set at 15.0% Brix. Two respondents provided reasons for abstaining from setting a limit for minimum colostrum quality. One reason was that the mother-bound impact of living immune cells and memory cells regarding diseases of the mother should be used, regardless of the quality of the maternal colostrum. Second, the other participant noted the importance of milking sufficient colostrum from cows, meaning that colostrum with a reduced IgG concentration is still preferable to no colostrum.

As shown in Figure 4.3, over one-third of participants (38.5%) obtained 1–5 L of colostrum per cow per milking, and another 39.2% obtained 6–10 L per cow. There were considerable differences in the amount of colostrum milked and ultimately fed to each calf.

Table 4.5 Descriptive overview of the data on participants freezing colostrum (FCR = freezing colostrum reserves; n = 130) and not freezing colostrum (NOR = no reserves; n = 16).

Variable	Category	FCR		NOR	
		Respondents, (n)	Proportion, (%)	Respondents, (n)	Proportion, (%)
From cows, in which lactation do/would you freeze colostrum?[1]	Lactation 1	27	20.8	0	0.0
	Lactation 2	56	43.1	6	37.5
	Lactation 3	85	65.4	6	37.5
	Lactation 4	85	65.4	5	31.3
	Lactation 5	78	60.0	5	31.3
	Others	0	0.0	4	25.0
What container would you consider suitable for freezing colostrum?[2]	PET reusable deposit	30	23.1	0	0.0
	PET disposable deposit	29	22.3	4	25.0
	ColostroBag	26	20.0	5	31.3
	Plastic can	13	10.0	1	6.3
	Freezer bag	9	6.9	2	12.5
	Plastic bucket	8	6.2	1	6.3
	PET canister unstable	2	1.5	1	6.3
	PET canister unstable	2	1.5	1	6.3
	PET canister stable	1	0.8	0	0.0
	Collection cup	1	0.8	1	6.3
	Glass bottle	0	0.0	3	18.8
	Ice cube tray	0	0.0	2	12.5
	Glass container	0	0.0	1	6.3
	Others	4	3.1	0	0.0
Where is/would your freezing option (be) located?[1]	Residence	79	60.8	11	68.8
	Milking parlor supply room	13	10.0	2	12.5
	Dairy Barn	11	8.5	2	12.5
	Office	8	6.2	2	12.5
	Recreation room	5	3.8	0	0.0
	Calf barn	4	3.1	0	0.0
	Forage kitchen	3	2.3	0	0.0
	Barn	2	1.5	0	0.0
	Machine hall	1	0.8	0	0.0
	Milking parlor	0	0.0	0	0.0
	Other premises	11	8.5	0	0.0

[1]Multiple answers possible for FCR group and NOR group
[2]Multiple answers possible for NOR group

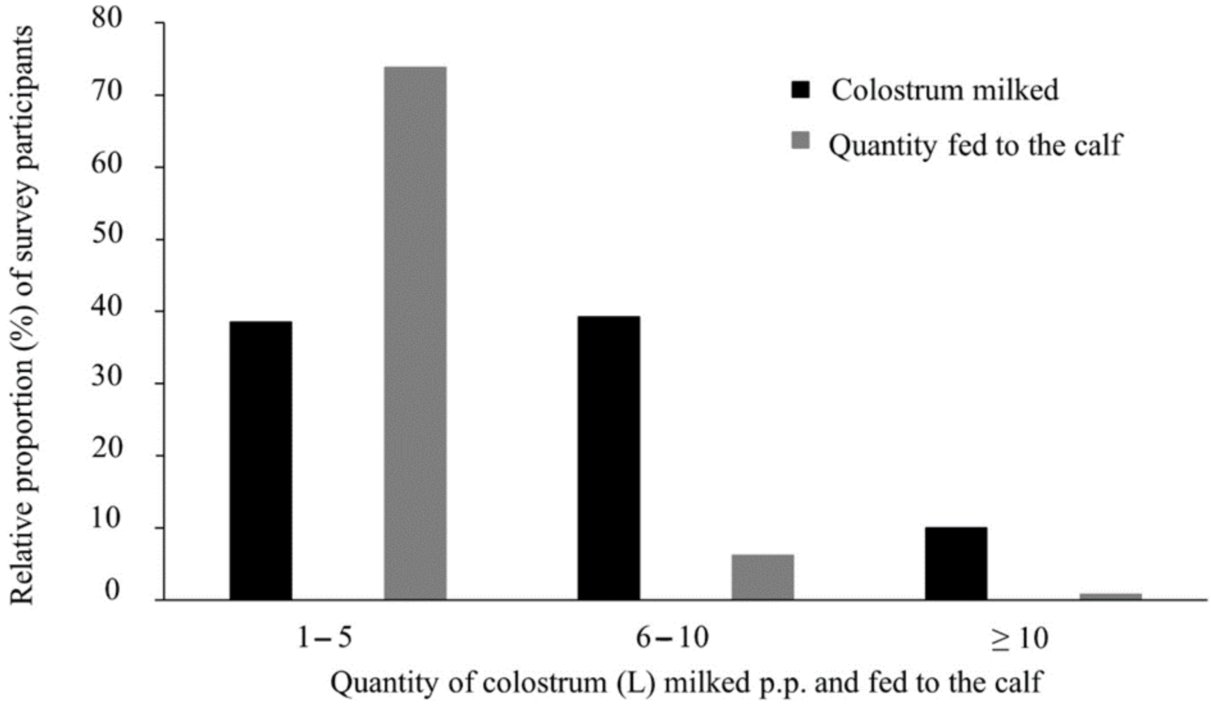

Figure 4.3 Comparison between the relative proportion of colostrum quantity milked in the first milking p.p. per cow (black) and the quantity of colostrum subsequently fed to the calf in the first feeding p.p. (light gray) based on the information provided by the survey participants.

At the first milking after birth, 39.0% of respondents milked 1–5 L of colostrum, while another 39.0% milked 6–10 L. In comparison, 73.8% of respondents fed 1–5 L at the first feeding, while 6.2% fed 6–10 L. The majority of calves received ≥ 4 L (42.3%), while 15.4% got < 4 L. Another 19.2% indicated a range of values both below and above 4 L (Min: 2 L, Max: 6 L) (Table 4.6).

Table 4.6 Overview of the amount of colostrum fed during the first feeding after birth of the participants who freeze colostrum (n = 130).

Variable	**Category**	**Respondents,** (n)	**Proportion,** (%)
How many liters of colostrum do you feed the calf in the first feeding p.p.?	< 4 L	36	27.7
	≥ 4 L	20	42.3
	< 4 L to > 4 L	25	19.2
	Not categorizable	14	10.8

No relationship was found between the quantity of colostrum fed and the variables level of education, sex and herd size. The respondents most commonly froze colostrum in portions of 0.5–2 L (62.7%), and 3.2% froze colostrum in portions of 1–4 L. Larger quantities of 2–4 L and 2–6 L were stored by 23.8% and 3.2% of participants, respectively. Approximately two-thirds stored one to five servings, and 13.5% stored between five and ten frozen colostrum servings. The majority (58.5%) kept the colostrum at temperatures ranging from −10°C to −19°C; 19.2% used temperatures ranging from −20°C to −29°C for storage. Among the respondents, 33.8% estimated the shelf life of frozen colostrum to be 6 months, 16.9% believed it could be used for up to 3 months, and 15.4% considered it viable for up to one year (Table 4.7).

Table 4.7 Descriptive overview of the data on participants freezing colostrum (FCR = freezing colostrum reserves; n = 130) and not freezing colostrum (NOR = no reserves; n = 16).

Variable	Category	FCR		NOR	
		Respondents, (n)	**Proportion, (%)**	**Respondents, (n)**	**Proportion, (%)**
Storage duration [month]	< 1	1	0.8	2	12.5
	1	3	2.3	0	0.0
	2	11	8.5	3	18.8
	3	22	16.9	4	25.0
	4	7	5.4	0	0.0
	5	2	1.5	1	6.3
	6	44	33.8	1	6.3
	7	5	3.8	0	0.0
	8	2	1.5	0	0.0
	9	0	0.0	0	0.0
	10	1	0.8	0	0.0
	11	0	0.0	0	0.0
	12	20	15.4	2	12.5
	> 12	3	2.3	1	6.3
	No at all	4	3.1	3	18.8
Thawing process[1]	Water bath bucket	62	47.7	5	31.3
	Professional water bath	18	13.8	5	31.3
	Cooking pot	14	10.8	0	0.0
	Outdoor temperature	6	4.6	2	12.5
	Room temperature	4	3.1	4	25.0
	ColostroMAT	2	1.5	1	6.3
	Microwave	1	0.8	1	6.3

[1]Multiple answers possible for NOR group

Respondents primarily used disposable PET bottles, reusable PET bottles, and ColostroBags. Of the participants, 60.8% stated that the freezing facility was in their home, and 10.0% stored frozen colostrum in the milking parlor supply room (Table 4.5).

Before freezing, 33.1% of the respondents investigated the IgG concentration in the colostrum. A moderately significant correlation ($P < 0.001$, r = 0.316) was calculated between farm size and the measurement of indicators of IgG concentration in colostrum before freezing, which was related to the fact that on larger farms, colostrum quality is more often determined before freezing. After thawing, 1.5% of the participants measured indicators of IgG concentration. One respondent recorded the IgG concentration after thawing but not before the actual freezing process. Of the survey participants who reported checking the IgG concentration in colostrum before freezing, 53.6% froze the tested colostrum only if a specific IgG concentration was determined. With the exception of four participants, the limits were stated as % Brix values. A limit of ≥ 22.0% Brix was used by 69.5% of participants. For 13.0%, the value was < 22.0% Brix, and the given range was enormous (14.0% to 29.0% Brix), so a value of at least 22.0% Brix was not guaranteed. A threshold in milligrams per milliliter was selected by 17.4% of the participants; the values chosen ranged between 35.0 mg mL^{-1} and 70.0 mg mL^{-1}, with the most-mentioned value of 50.0 mg mL^{-1}. One respondent suggested a 20.0–30.0% Brix range as the decision limit for further feeding of thawed colostrum.

Most of the colostrum was thawed in a water bath: 47.7% in a bucket and 13.8% in a professional water bath. Another 10.8% of the frozen colostrum was heated in a cooking pot (Table 4.7). The time and temperature required to thaw frozen colostrum portions differed depending on the method used. The thawing time ranged from 10 min to 120 min when a bucket was used (39.5 ± 26.7 min). Temperatures of water in the bucket ranged from 25°C to 65°C with an average of 43.6 ± 8.2°C. In a professional water bath, the thawing time ranged from 20 to 180 min (69.3 ± 39.7 min), with temperatures varying from 35°C to 50°C (39.9 ± 3.3°C). Heating the colostrum in a cooking pot lasted between 10 min to 120 min (36.9 ± 27.6 min) at temperatures ranging from 30°C to 80°C (45.7 ± 13.1°C). As shown in Figure 4.4, temperatures < 45°C were predominantly used to defrost the colostrum in all three methods. Of respondents who thawed colostrum at temperatures between 45°C and 60°C, a greater proportion used a bucket or cooking pot than a professional water bath. Temperatures > 60°C were observed in the cooking pot more frequently than in the bucket but not in the professional water bath.

Figure 4.5 depicts the temporal aspects of thawing. Thawing colostrum in a water bath at temperatures < 45°C required either 20 min to 30 min or 31 min to 60 min. The thawing time was less than 20 min at temperatures between 45°C and 60°C. The time required in the professional water bath was the same at temperatures < 45°C and from 45°C to 60°C, which was primarily within the range of 31 min to 60 min. The participants did not indicate temperatures > 60°C. Defrosting in the cooking pot took 20 min to 30 min at temperatures < 45°C and between 20 min to 30 min or 31 min to 60 min at temperatures between 45°C and 60°C.

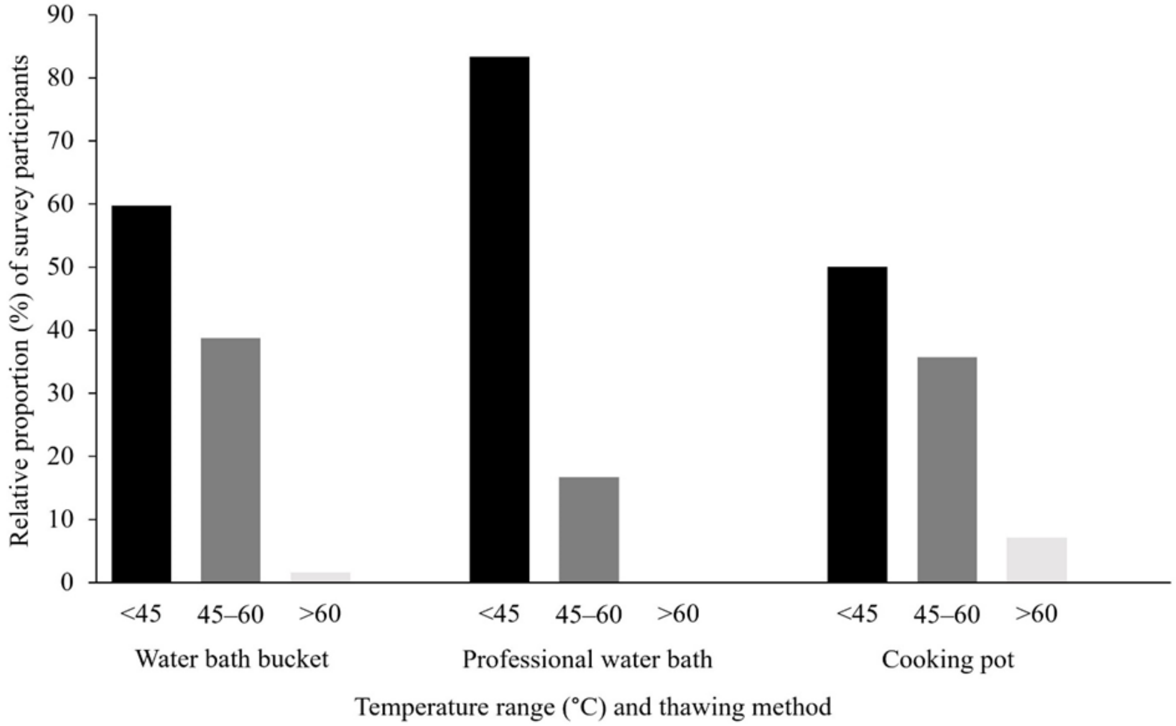

Figure 4.4 Distribution of survey participants in the FCR group among the three most common thawing methods: 1. Water bath bucket (n = 62), 2. Professional water bath (n = 18), 3. Cooking pot (n = 14) divided by the temperature (°C) at which the colostrum was thawed.

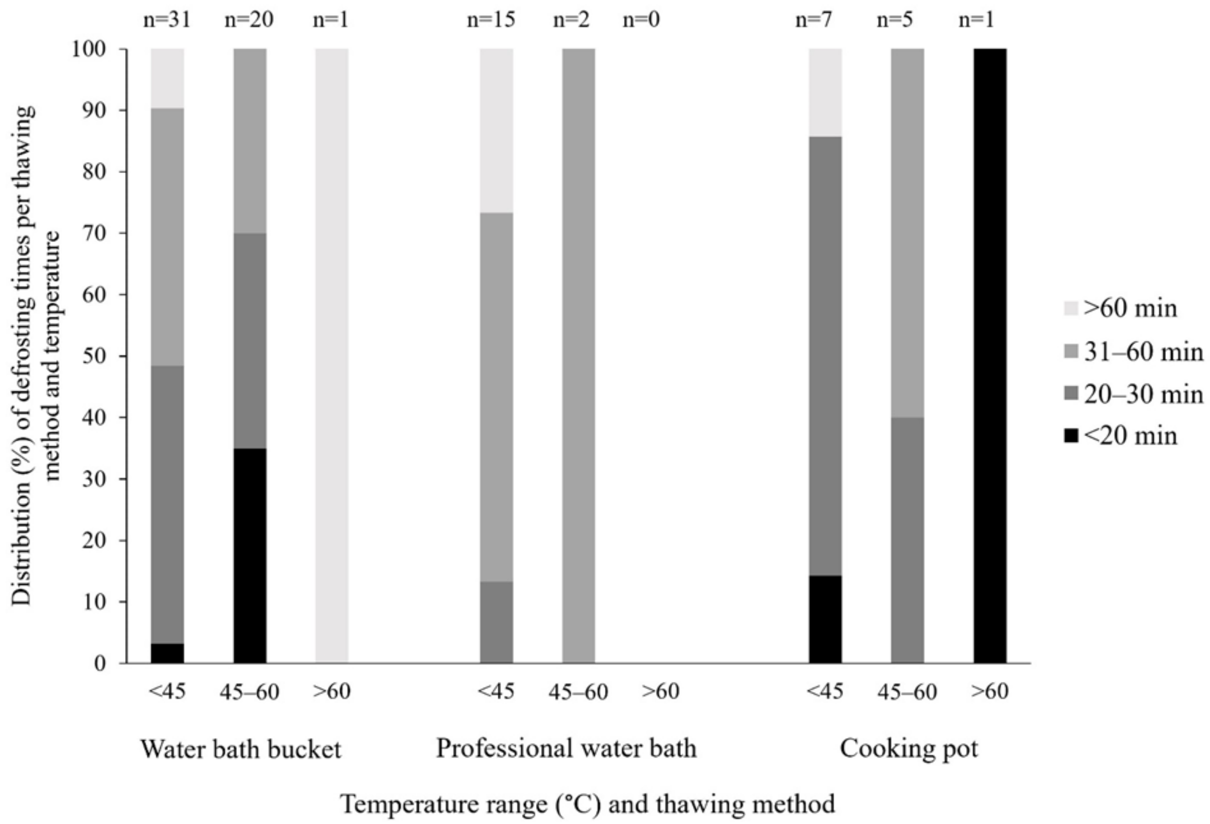

Figure 4.5 Distribution of survey participants from the FCR group according to the defrosting method subdivided by temperature (°C) and the respective defrosting duration [min].

4.3.5 Colostrum Management by Respondents who did not Freeze Colostrum

Colostrum was not frozen by 16 participants. No relationship was found between herd size and the freezing or non-freezing of colostrum reserves. Of the 16 participants, 50.0% stated that the creation of a colostrum bank was too labor-intensive for them to implement on their farm. Farms that did not freeze colostrum due to additional labor (n = 8) were equally divided between those with < 100 cows and those with ≥ 100 cows. Another 56.3% relied on colostrum from other cows instead of frozen reserves. In 66.7% of cases, farms that cited this reason (n = 9) had a herd size of ≥ 100 cows. 12.5% of the respondents considered that there was no benefit in keeping a colostrum bank. In the hypothetical questions posed, 37.5% of these 16 respondents would freeze colostrum from cows during their second and third lactation, whereas 31.3% would prefer colostrum from cows during their fourth or fifth lactation (Table 4.5). Moreover, 31.3% would choose ColostroBags as containers, whereas 25.0% would freeze colostrum in PET disposable deposits. The majority (68.8%) would have access to a freezing unit at home; 12.5% would use a freezing unit at the dairy barn, milking parlor supply room, and office. In addition, 12.5% would keep frozen colostrum for less than 1 month, 18.8% for up to 2 months, and 25.0% for up to 3 months, whereas 12.5% would expect a shelf life of at least one year (Table 4.7). Preferred thawing methods would include water bath buckets (31.3%), professional water baths (31.3%), and room temperature (25.0%). Refrigeration instead of freezing would be an option for 25.0%. There was a trend that participants with higher educational attainment were more likely to accumulate colostrum reserves (P = 0.054).

4.4 Discussion

4.4.1 Characteristics of the Survey Respondents

The survey's gender distribution differed from the average in German agriculture (Federal and State Statistical Offices, 2021). The study by Smith (2008) supports the higher number of female participants, as women tend to participate in surveys more frequently than men. Additionally, the survey results indicate a trend toward female participation in calf rearing as opposed to farm labor, which is still predominantly performed by males. Enticott et al. (2022) concluded that female employees are essential to calf rearing. Research suggests that female caregivers can have a positive impact on colostrum management, leading to improved calf health. According to Lensink et al. (2000), women exhibit greater patience in calf care, which is reflected in their handling of newborn calves. Additionally, Wilson et al. (2023) found that women tend to make fewer distinctions in the care of bull or heifer calves. However, different studies have shown that the proportion of male employees feeding calves or working as stockmen in German agriculture is still higher than the proportion of female employees similarly employed (Phipps et al., 2016; Hayer et al., 2021).

In the current study, the proportion of 20–29-year-olds was significantly higher than that reported in previous studies (Mahendran et al., 2022; Johann Heinrich of Thünen Institute et al., 2023). The dissemination of the survey through university channels has influenced the age structure of respondents, although internet access and social media use may have also had an impact (Mahendran et al., 2022; Ractham et al., 2022). It can be assumed that people with digital skills are more likely to participate in an online survey than people who have difficulty with it. These aspects also affect the distribution of educational qualifications. The participant's level of education corresponded to the distribution of those employed in German agriculture. However, the percentage of people who have graduated from agricultural business management was only one-third of the national average. Conversely, the number of university degree holders exceeded the national average by 10.0% (Federal Statistical Office of Germany, 2021a). In the survey by Hayer et al. (2021) performed in Germany, the proportion of university degrees was also above the national average (19.1%). The survey circulation in North Rhine-Westphalia may have influenced the distribution of participants, with slightly lower participation from Bavaria and Baden-Württemberg (Federal Statistical Office of Germany, 2021b).

4.4.2 General Farm Characteristics

A comparison with the national distribution (Federal Statistical Office of Germany, 2021b) and the study of Dachrodt et al. (2022) showed that the distribution of participants relating to the production system was consistent with the national average. The number of participants was half the national average in the 20–49 cow category and twice the national average in the 100–199 cow category. Furthermore, in the 200–499 cow category, a score four times higher than the national average was recorded. The proportion of respondents who managed farms with more than 99 cows was higher than that recorded nationally, explaining the significant difference in the average herd size (Federal Ministry of Food and Agriculture, 2021). Quantitative analysis revealed that the average number of cows per farm was significantly higher than the national average (147 vs. 71). Kehoe et al. (2007) stated that smaller farms have better colostrum management, but our survey could not confirm this. Hayer et al. (2021) found that increased numbers of cows resulted in an overload of additional calves, and this situation was attributed, in particular, to additional strong, individual care of the calves. In such cases, colostrum management may also become critical. Klein-Jöbstl et al. (2015) did not find differences in the time to first feeding and the quantity of colostrum at the first feeding p.p. between small (≤ 20 cows) and large farms (> 20 cows). Our study also found no difference in the quantity of colostrum at the first feeding between small and large farms. However, larger farms appear more open to scientific advice (Hoe and Ruegg, 2006) and use consultative services specialized in animal health (Russell and Bewley, 2013). These findings indicate that colostrum management on larger farms is being actively adapted and improved.

Several respondents performed a variety of farm tasks frequently or very often. Only a few respondents specified certain tasks or work complexes. Farmers perceived good colostrum management as time-consuming, as discovered by Palczynski et al. (2020). This statement explains why participants in our survey who spent a large proportion of time on calf-related tasks allocated less time to other tasks. It became clear that farmers focusing on calf rearing performed well at colostrum management. Individuals who performed numerous other tasks encountered difficulties maintaining high quality for all tasks. A clearly defined role in calf rearing was viewed favorably because it allowed more time to be spent on the calves and continuous observation. Responsibilities should be communicated and implemented (Vaarst and Sørensen, 2009; Palczynski et al., 2020). Time management, a sense of control, and confidence in abilities are critical in keeping low calf mortality within the complex structure of herd management and calf rearing (Vaarst and Sørensen, 2009; Hayer et al., 2022). Flexibility is required to react to spontaneous problems (Vaarst and Sørensen, 2009), but maintaining this flexibility can be difficult if the person is involved in multiple tasks. Therefore, to save time, tasks such as measuring indicators of IgG concentration in colostrum or freezing colostrum reserves may not be performed. The results of the recent survey also indicate this aspect, as participants with a stronger focus on calf husbandry tend to freeze and monitor IgG concentration more frequently.

However, the survey results show that there is a general work overload regardless of the farm's size. On farms with more employees, assigning specialists for calf-related tasks is possible. Their responsibility is focused only on the care and rearing of calves, which means that calf-specific tasks are performed more accurately and by the same staff (Palczynski et al., 2020). As farms grow and the number of animals per farm increases, the number of nonfamily workers also increases (Barkema et al., 2015). Communication between different employees responsible for the same tasks gets more important. In addition, as the hiring of non-native speakers becomes increasingly prevalent on large farms, communication becomes even more challenging (Schenker and Gunderson, 2013). In our study, the number of employees per farm was between two and three. However, in this area, clear work instructions and agreement would ensure better colostrum management and improved calf health because insufficient employee training is associated with poorer animal handling and calf management (Schuenemann et al., 2013).

No difference in colostrum management was found between farms with a conventional milking parlor and farms with an AMS, which aligns with the results of Robbers et al. (2021a). Nevertheless, using an AMS impacts people's work tasks and roles. Time-consuming work is completed automatically, freeing up time for other tasks. An AMS can help to improve the flexibility mentioned above, which benefits calf rearing (Butler et al., 2012).

4.4.3 Colostrum Management

In recent years, the definition of colostrum has shifted. In the research by Blum and Hammon (2000), the first to sixth milking was referred to as colostrum; however, the term now refers primarily to the first milking, with everything subsequently designated as "transition milk" (Godden et al., 2019). However, similar to our survey, most respondents from the study by Robbers et al. (2021a) considered the first milking (47.0%) or the first to third milking (41.0%) p.p. to be colostrum. The distinction between colostrum and transition milk has not yet been completely adopted in German practice. It can, therefore, be assumed that the respondents were unaware of the reasons for the division into colostrum and transition milk regarding the ingredients and the changes in milk composition. Nevertheless, transition milk is superior in value to milk for newborn calves because its composition continues to vary widely. Even though the Ig concentration is lower in transition milk than in colostrum, it is still elevated relative to milk in general, as are other milk components that should be provided to the calf.

Following the statement of Staněk et al. (2014), inadequate or no colostrum storage indicates insufficient knowledge of the importance of colostrum storage for the timely and adequate feeding of colostrum to newborn calves. Colostrum storage includes freezing, refrigeration, and storage at room temperature. Different procedures affect different parameters and ingredients in the colostrum. In addition to storage, the duration and temperature of storage affect the composition of colostrum. After milking, colostrum should be fed, cooled, or frozen as soon as possible (Godden et al., 2019). Storage at room temperature leads to faster proliferation of bacteria in colostrum (Stewart et al., 2005) and a higher risk of bacterial contamination (Johnson et al., 2007). Most European farmers understand the importance of colostrum reserves (Balthazar et al., 2015; Klein-Jöbstl et al., 2015; Cummins et al., 2016). In this survey, the proportion of participants freezing colostrum was also very high. In another German study, the proportion was similarly high, at 78.0% (Hayer et al., 2021). Although Cummins et al. (2016) indicated that freezing was performed less frequently on farms with larger herds (> 20 cows) than on farms with smaller herds (≤ 20 cows), Klein-Jöbstl et al. (2015) determined the opposite. According to several studies (le Cozler et al., 2012; Staněk et al., 2014; Barry et al., 2019), many farmers store colostrum. Nonetheless, some studies did not specify how and for how long colostrum is stored (le Cozler et al., 2012), and some stated that colostrum is often stored at room temperature (Cummins et al., 2016; Phipps et al., 2016; Barry et al., 2019; Robbers et al., 2021a). Vogels et al. (2013) discovered that keeping colostrum at room temperature before feeding occurs frequently in Australia. Colostrum is also frequently kept in the refrigerator and not frozen (Cummins et al., 2016; Phipps et al., 2016; Barry et al., 2019). Fresh colostrum should be refrigerated or frozen as quickly as possible if it is not fed directly to the calf. Refrigerated colostrum remains suitable for use for up to a duration of 12 h post-milking; however, it is not recommended for use beyond this timeframe (Hopper, 2021). Raw, refrigerated colostrum can maintain stable IgG levels for at least one week. However, the bacterial count in this colostrum can reach unacceptably high concentrations, exceeding 100,000 cfu ml^{-1}, after two days of refrigeration (Stewart et al., 2005).

Numerous studies have investigated the influence of lactation number on colostrum quality, and a correlation has been found between IgG concentration and lactation number (Ahmann et al., 2021). Although it has been scientifically proven that the colostrum of first-calf cows may contain less IgG, farmers often feed colostrum from first-calf cows without measuring the IgG concentration. In a Czech study, 45.6% of cows were always fed the colostrum of first-lactation cows, and it was provided occasionally to 46.3% of cows (Staněk et al., 2014). In Germany, colostrum from first-calf heifers was often fed to calves (83.3%), with little control over colostrum quality (23.8%) (Hayer et al., 2021). In our survey, FCR and NOR farmers froze colostrum from first-lactation cows to a lesser extent or did not freeze it. However, only just over half of the respondents from FCR group who fed colostrum from cows in the first-lactation tested the Ig concentration.

Information on the quantity of colostrum that should be fed during the first feeding p.p. varies between studies. Most studies suggest 4 L of colostrum, but the feeding recommendation has recently changed to a weight-related specification of 10.0–12.0% of the calf's body weight (Godden et al., 2019). Morin et al. (2021) mentioned a minimum of 2.5 L to achieve sufficient passive immunization because the percentage of calves with sufficient immunization that received at least 2.5 L was 2.6 times higher than that of calves that received less than 2.5 L of colostrum. However, only 19.0% of the calves in the study by Morin et al. (2021) received at least 4 L of colostrum, similar to Vasseur et al. (2010), where 25.0% of calves were fed at least 4 L. The value in our study is similar at 26.9%, but this only includes the participants feeding 4 L of colostrum. If the participants who fed ≥ 4 L are included, the value rises to 42.3%, which is significantly higher than the values from the other studies. Various studies have shown that feeding < 3 L of colostrum is still common worldwide (le Cozler et al., 2012; Cummins et al., 2016; Barry et al., 2019). Hayer et al. (2021) found that colostrum feeding was primarily restrictive (72.5%), with

35.0% of respondents feeding a minimum of 3 L on German farms. In Klein-Jöbstl et al. (2015), 71.9% of respondents provided between 2 L and 4 L during the first feeding. The authors found no differences between small and large farms.

Freezing and thawing play an important role in colostrum management because both processes can negatively influence the content of the various components of colostrum (Robbers et al., 2021b). Negative influences that reduce important ingredients should be minimized. The negative impact of freezing colostrum at −20°C on IgM and IgG levels was reported (Abd El-Fattah et al., 2014). The concentration of IgM decreased to 10.8% and that of IgG to 74.1% after frozen storage for 6 months. The authors recommend that colostrum should not be stored for over 3 months at −20°C (Abd El-Fattah et al., 2014). However, according to Hopper (2021), colostrum can be safely stored at −20°C for up to a year before reuse. Most respondents in our study specified a temperature lower than −20°C. We found differences in the storage duration of colostrum between the two groups. The NOR group would contemplate storing frozen colostrum for a significantly shorter period (< 1 month to 3 months), whereas the storage period in the FCR group was most often 6 or 12 months. All respondents who operated at a temperature of −20°C or below froze the colostrum for over 3 months. Only a few studies have examined the shelf life of frozen colostrum, especially under various conditions. Furthermore, there is limited information about the reactions of other relevant substances next to Ig. To ensure proper handling and storage, it is important to provide this information in an easy-to-understand way. The quality and effectiveness of stored colostrum would also significantly benefit from better communication between scientists and farmers.

A difference between the two groups (FCR vs. NOR) was evident in the vessels used for freezing. The 16 participants in the NOR group would mainly consider using ColostroBags and disposable PET deposits. The FCR group used PET disposable and PET reusable deposits, which the NOR group did not select. However, ice cube trays, freezer bags, and zip freezer bags were more favored in the NOR group. A divergent perception of the implementation of freezing occurs between the two groups. The most commonly used containers in the study by Robbers et al. (2021a) were sealed and open buckets. However, the containers for storing colostrum, not just those for freezing colostrum, were examined. Any plastic container can be used to freeze colostrum reserves, such as bottles or bags, with a volume of 0.5 L to 2 L (Balthazar et al., 2015). However, the shape of the container affects the storage capacity. Plastic bags can be stored flat in the freezer and stacked, and frozen colostrum can be defrosted and fed more quickly when it has a flat surface. The vessel not only affects the storage capacity but also impacts the thawing process. Because the shape and volume of the containers affect the speed of the freezing and thawing process, an optimal procedure can save time. If thawing is too long (> 1 h), it can delay feeding and thus the absorption of the urgently needed Ig. In addition, it makes sense for hygienic and nutritional reasons to freeze and thaw quickly. If the processes are too slow, hygiene and nutrients of the colostrum can be negatively affected. However, the influence of the container's shape and volume on freezing and thawing is known to only a few farmers and should be investigated in further studies to present a best practice to farmers. Concerning the placement of the freezer unit, the participants in both groups unanimously placed it in an apartment building, dairy barn, milk service room, or office. In terms of labor economy, the freezer should be installed as close to the point of usage as possible, but the milk service room often lacks the required hygiene and space to establish a freezer on small farms. In many cases, only a few portions of colostrum are frozen; therefore, investing in a separate freezer is not cost-effective. Consequently, farmers frequently use their home freezer to preserve colostrum. This method of storage is also not optimal for food and feed safety reasons, as food contamination can occur.

The number of farms routinely testing colostrum quality varies between studies (12.8% to 44.1%) (Staněk et al., 2014; Barry et al., 2019; Robbers et al., 2021a). Our study recorded a colostrum quality measurement of 33.1%, which falls within the expected range. Although the recorded value exceeds the minimum value of 12.8% reported in the literature, it is still insufficient. To ensure an adequate colostrum supply, a significantly higher proportion of farmers should measure colostrum quality. While most farmers understand the significance of colostrum management, measuring colostrum quality in this context appears to be unfamiliar. It is crucial to address this gap promptly to ensure that colostrum quality is regularly monitored on more farms. Klein-Jöbstl et al. (2015) recorded significantly higher values, with small farms (80.3%) performing better than larger farms (77.7%). The optimal IgG concentration also varies between studies but is generally greater than 20.0% Brix (Ahmann et al., 2021). Morin et al. (2021) discovered that calves fed colostrum with 25.5% Brix had an almost three times higher percentage of adequate passive immunization than those fed colostrum with a lower IgG concentration.

Thawing in water baths is widely used and considered a good method to thaw frozen colostrum carefully. Cummins et al. (2016) reported that 64.0% of farmers used a water bath to defrost colostrum. However, temperature must be considered during the thawing process. Very high temperatures (≥ 60°C) appeared to have a negative effect on IgG concentration in colostrum, regardless of the defrosting time (Balthazar et al., 2015; Elizondo-Salazar et al., 2010; Elsohaby et al., 2018). The participants in our study mainly heated the colostrum at < 45°C or temperatures between 45°C and 60°C. Nevertheless, one person stated that they thawed the colostrum at over 60°C. Balthazar et al. (2015) suggested that the optimal water bath temperature range is between 40°C and 60°C, as temperatures > 60°C result in IgG1 losses of 20.0–25.0%. The temperature at which colostrum is fed is important because if it is too low, thermoregulatory effects will negatively impact feed intake. On the other side, proteins denature at a temperature of ≥ 40°C, which is why such high temperatures must be avoided. Therefore, a temperature of ≥ 35°C, not exceeding 39°C, is recommended for feeding colostrum in Germany and the corresponding climate. In particular, thawing at room temperature rarely achieves temperature values that positively affect feed intake.

Thawing time can be decreased using a microwave, but only with a loss in Ig concentration. A change in wattage, from 200 W to 305 W, increased the loss of IgG1 from 20.0% to 31.0% (Balthazar et al., 2015). In addition, microwave use can negatively influence other colostrum components (Robbers et al., 2021b). For the respondents in our survey, microwaves were almost not an option despite the time savings. In contrast, the pasteurization of colostrum is advantageous because a considerably reduced bacterial count was observed in heated colostrum compared with raw colostrum. In addition, the 24-hour serum total protein and IgG concentrations were higher in calves that received colostrum with heat treatment. A positive influence was also observed on the absorption efficiency of IgG (Johnson et al., 2007).

To maintain optimal IgG concentration, it is advisable to thaw colostrum within the temperature range of 40°C to 60°C, for example, in a water bath. Thawing at temperatures > 60°C in a cooking pot can result in significant losses of IgG1, which can adversely affect the quality of the colostrum. A cooking pot has no temperature control, making it difficult to achieve the right temperature for thawing. Although microwaves offer time-saving benefits in thawing colostrum, it is important to note that this method may lead to a loss in Ig concentration, especially with higher wattages. Moreover, microwaves can also negatively affect other colostrum components. In particular, heat spots that occur in colostrum when using microwaves cause problems. Therefore, it is recommended to avoid using microwaves and cooking pots for colostrum thawing and use water baths instead. However, the question arises if the colostrum should be thawed slowly to avoid Ig loss and therefore feed the colostrum 2 h later, or should a loss of Ig be accepted in order to feed the colostrum as quickly as possible? It is not yet clear which of these aspects is more important, so further research is needed to inform farmers of the best practices.

4.4.4 Study Limitations

Of the 54,677 registered dairy farms in Germany in 2021 (Federal and State Statistical Offices, 2021), only 0.3% of the farmers responded to the survey. The authors of the study are aware that the number of participants is small compared with the total number of German dairy farmers. Because of the relatively small number of participants, the collected data cannot be generalized to all German dairy farmers. Few studies have considered the process of freezing colostrum in Germany, despite its importance as an essential part of colostrum management and calf rearing. This study has provided first insights into the freezing process and useful information about freezing colostrum reserves on German dairy farms. Subsequently, further research questions and aspects of knowledge transfer have arisen. Current knowledge gaps and the development potential can be defined. Furthermore, the results of this study extend the current research on colostrum management on German dairy farms.

4.5 Conclusions

This study aimed to provide an overview of colostrum management practices on German dairy farms, with a particular emphasis on colostrum storage in freezing units. Most respondents were aware of the importance of colostrum management in calf rearing. Moreover, most respondents attached sufficient importance to the storage of frozen colostrum reserves. Nevertheless, not all respondents created a colostrum bank, citing the increased workload. Furthermore, there are no specific recommendations for storing and thawing frozen colostrum reserves. Overall, freezing colostrum can provide farmers with a reliable and convenient way to ensure that newborn calves receive the essential nutrients and immunity for optimal health and growth. In this context, farmers and employees must be educated and targeted knowledge transfer is required. In this way, standard operating procedures can also be developed to support the optimal implementation of colostrum management. The influencing elements surrounding colostrum storage, such as the thawing process or testing for IgG concentration, may, therefore, be positively modified. Through better management, healthy calves grow into long-lived, productive dairy cows.

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5 General Discussion and Conclusions

Numerous factors affect calf health and welfare, with varying impacts on the different elements of calf rearing. The influencing variables should be focused on having a favorable effect on the calf, as they are the cornerstone of every successful dairy farm. Studies have consistently shown that improving calf management should be a priority in Germany and other countries with a large number of dairy farms (Gulliksen et al., 2009; Abuelo et al., 2019; PraeRi, 2020). The high mortality and morbidity rates observed in the case of Germany indicate the necessity for farmers, veterinarians, and scientists to address management issues in calf rearing (PraeRi, 2020; Hayer et al., 2021). Calves are born with insufficient immune competence and, therefore, cannot defend themselves against pathogens during the first weeks of life (see Section 2.1.1). The cow's placenta acts as a barrier to the transfer of macromolecules, including Igs. Consequently, the transfer of these molecules via the placenta before birth is not possible. Passive immunization occurs through oral uptake of the mother cow's antibodies, ensuring the protection of the calf (Becker and Märtlbauer, 2016). Due to this elementary process, colostrum management tremendously impacts calf health in the early phase of life and the development from calf to cow, as well as the cow´s overall lifespan (see Section 2). Furthermore, proper colostrum management is crucial due to emerging economic and animal welfare implications. FPT rates can serve as an indicator for assessing colostrum management. The significance of FPT and its consequences are widely recognized and have been extensively researched (Atkinson et al., 2017; Godden et al., 2019). However, the high prevalence of FPT in different studies (Table 2.3) also indicates a need for improvement in colostrum management. The progress will lead to better overall calf management and welfare (Elsohaby et al., 2019; da Costa Corrêa Oliveira et al., 2019; Sutter et al., 2020).

This thesis presents the factors of colostrum management in greater depth. Research has been conducted on aspects of colostrum management, and two studies – found in the Sections 4 and 5 – have published specific findings. Study 1 reviewed the various factors that influence colostrum quality in terms of Ig concentration. At the same time, it was made clear that multiple methods already exist to measure the highly variable Ig concentration in colostrum. However, only a small part of these methods can be directly applied by farmers or their employees, as most of the methods can only be used in the laboratory. In addition, there are time- and effort-specific factors that should be kept as low as possible.

Furthermore, a survey was conducted to gain insight into colostrum management on German dairy farms, and the results were published as part of Study 2. The aim of the survey was to identify further areas for improvement in colostrum management. As the second study showed, the importance of good colostrum management is well known by farmers. Most participants measured the Ig concentration of the colostrum they fed directly to newborn calves. However, the study showed room for improvement in some standard areas of colostrum management. In particular, the freezing of colostrum to allow immediate feeding in emergency situations revealed knowledge gaps and enormous potential for improvement. Denholm (2022) concluded that further research is needed on both established and new methods for preserving colostrum. Freezing is mentioned as an example, and optimal temperature and storage time should be investigated to optimize the procedure and then communicated to farmers. Improvements in colostrum management, such as freezing colostrum reserves, could positively impact mortality and morbidity rates in calf rearing (see Section 2). Appropriate colostrum management significantly impacts calf development, and studies indicated that many farms need to improve in this area to implement best practices (Kehoe et al., 2007; Vasseur et al., 2010; Morrill et al., 2012).

The knowledge of colostrum management related to the factors influencing the substances in colostrum and the high quality of colostrum is available (Study 1). Nevertheless, effective knowledge transfer to the farmers failed, according to the results of Study 2. These results highlight the necessity for improved processing and dissemination of scientific research findings to farmers on a broader scale. Moreover, there is a critical need for better integration and application of this knowledge within farm work organizations to optimize colostrum management and calf rearing practices. Colostrum management is a significant topic in scientific research, with guidelines and thresholds established to support appropriate management. However, due to lack of awareness, knowledge, time or motivation, farmers often fail to implement scientific advice to the required extent. Improving colostrum management involves identifying the reasons for not implementing recommendations (Palczynski, 2021) and areas where scientific advancements are still needed, such as knowledge transfer.

Figure 5.1 shows the network between science, consulting, and practice, in which work organization, knowledge transfer and data management lead to an adequate colostrum supply for the calf. This, in turn, enables healthy calves to be reared as long-lived and productive dairy cows. In order to achieve this goal, it is essential that the scientific community, including universities and research institutes, disseminate their findings and knowledge to agricultural extension organizations and veterinarians. Then these organizations can process the knowledge and results for knowledge transfer and implement them in practice. It is also crucial that the scientific community considers the target group-oriented preparation of the knowledge and results when carrying out their own knowledge transfer. A pure transfer of scientific knowledge would not be as effective. Concurrently, the necessity for further research can be conveyed to the scientific community by both direct engagement with farmers and through the intermediary of advisory organizations. Joint events can serve as a platform for targeted exchange between the three groups.

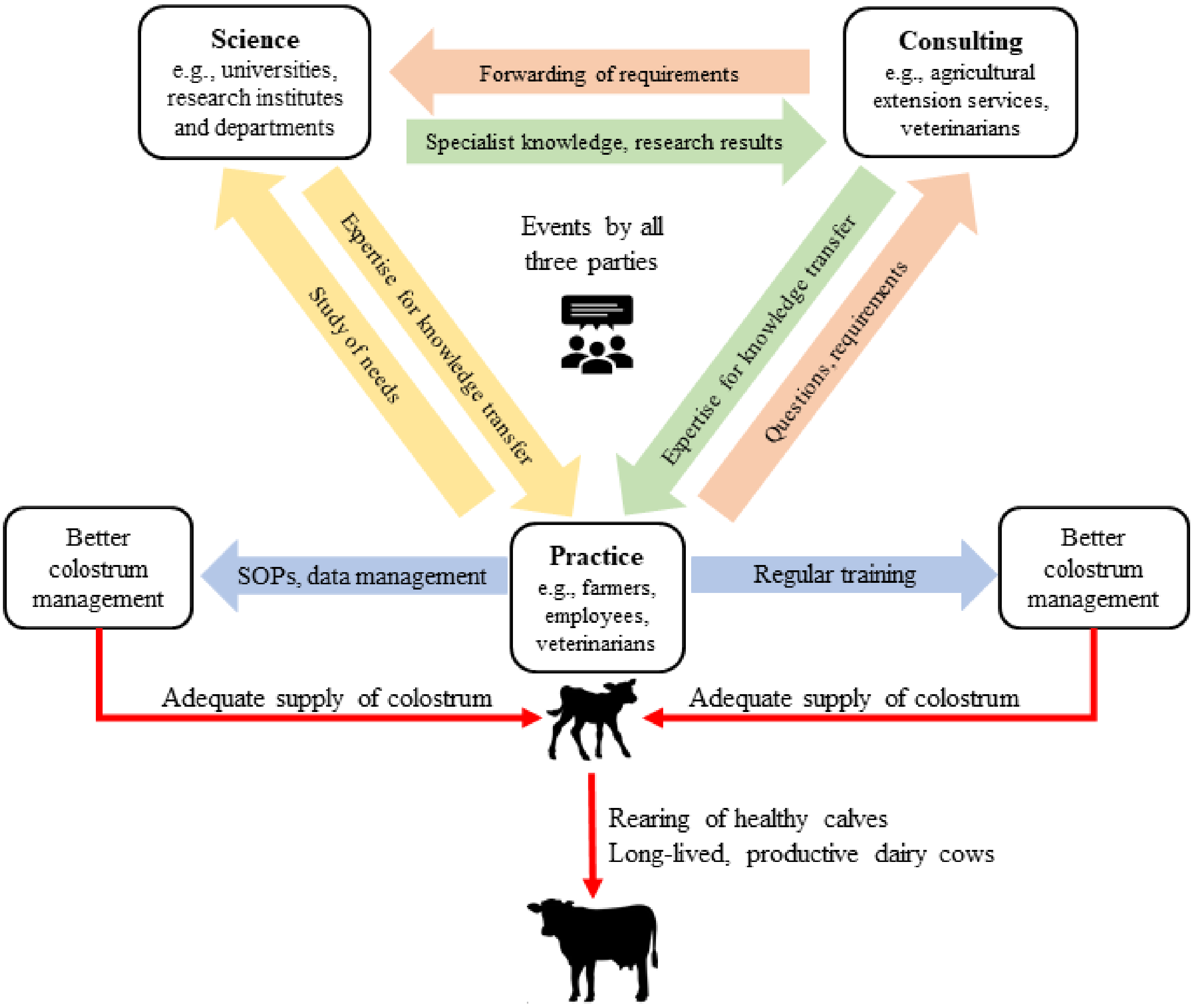

Figure 5.1 Linking between science, consulting and practice to improve colostrum management through organization, knowledge transfer and data management.

Knowledge dissemination to farmers, agricultural employees, or veterinarians can facilitate the optimization of colostrum management through the implementation of SOPs and data management. Regular training of those involved, also by advisory organizations, can achieve a similar outcome. The result is a sufficient supply of colostrum for the calves, which in turn has a positive effect on calf rearing.

The following sections will discuss three problem areas mentioned in the literature overview and studies of this dissertation: work organization, knowledge transfer and data management. The aim is to critically examine these points in the context of enhanced colostrum management and identify potential areas for improvement. Work instructions, management changes, and critical control points will be emphasized in the framework of enhanced colostrum management on German dairy farms.

5.1 Work Organization for Better Colostrum Management

Business management tools can be used to implement a structured work organization on dairy farms. These tools include organization charts, job descriptions, work and shift schedules, and SOPs (see Section 2.4). They can be applied to agricultural livestock farming. Additionally, the farm manager should establish operational communication that standardizes the exchange of information between the farm´s external consultants, veterinarians, and inseminators, which is crucial to the farm's success. However, the introduction and implementation of work organization on dairy farms will always remain an individual farm solution due to the extensive structural differences, such as operational goals, technical equipment, basic feed production, calf rearing, and management (Buschsieweke et al., 2016). The objective is to implement best practices that achieve the optimal outcome for each calf despite the numerous challenging aspects of calf rearing (e.g., high workload, language barriers, poor training).

Implementing new practices requires an understanding of both the individual farm situation and the various factors that influence farmers' behavior. Rose et al. (2018) summarized the components into seven key factors: (1) personal factors such as age, gender, experience, education, attitudes, and beliefs; (2) business factors such as farm size, cash flow, number of employees, succession plans, and profitability; (3) family, peer, and advisor network; (4) sense of control over the decision and confidence in adopting a new practice; (5) incentives or rewards; (6) market or compliance-based rewards; and (7) information provision, education, and clear communication. These factors should also be considered when setting up farm-specific SOPs for colostrum management. Therefore, SOPs should not be unthinkingly copied from other farms; instead, adjustments to farm-specific management factors are necessary. Nonetheless, there are currently several SOPs and recommendations available online for managing colostrum and raising calves, which may provide a starting point for creating farm-specific SOPs. The 5 Q’s mentioned in Section 2.2 also serve as a good orientation guide and starting point to define SOPs for colostrum management (e.g., recording of colostrum quality). It was also shown that the implementation of SOPs already developed for calf rearing for different tasks was rated as high by different farm managers for their own farms (n = 1,074, 66.5%). These results showed that existing SOPs can be used on different farms despite different farm situations and that only minor adaptations may be necessary (Neukirchner et al., 2024).

The establishment of SOPs can meet the increasing consumer demand for transparency in the production process. SOPs ensure a controlled, consistent and transparent production process that meets the goals and standards of German dairy farming, including calf rearing (Manghani, 2011; McCrea, 2005). Ensuring that each employee is aware of their responsibilities is especially important on large farms that use shift systems for calf rearing, which includes cleaning, feeding and treating sick calves. In addition, research has shown that different employees perform the same tasks differently (Hesse et al., 2017), which can lead to divergent outcomes. At the same time, consistency on dairy farms is a prerequisite for a successful farm (Stup, 2017).

Practical instruments such as refractometers and colostrometers can be used on the farm to estimate Ig concentrations. These methods are simpler and faster, but less accurate than direct methods such as ELISA (Study 1). If the measurement of Ig concentration in colostrum is to be incorporated into the routine of colostrum management, it is essential that the personnel conducting the measurement are fully aware of the necessary steps to perform the measurement correctly. First, the necessary equipment must be purchased (e.g., refractometer) and then detailed instructions on the correct handling of the device must be provided to all employees. Therefore, professional training should accompany the implementation. In order to ensure the reliability of the measured results, proper usage of the measuring device is necessary for the assignment to be completed successfully. Simultaneously, uniform limit values should be defined so that different employees meet the same specifications for “good” and “bad” colostrum. As demonstrated by Study 2, there is a lack of awareness regarding the limitations of high-quality colostrum and where those limits are based on the method of measurement. In practice, however, it is important to find the best possible compromise. This means that “bad” colostrum is still better than no colostrum at all. If there are no reserves that meet the limits for “good” colostrum, and the calf was born hours ago, these limits must be disregarded and colostrum of lower quality must be used.

The implementation of a SOP for the routine measurement of Ig concentration in colostrum, using a refractometer or alternative techniques (Study 1), could be documented in an easy-to-follow step-by-step format. An example is included in the appendix (Section 6). This format could be used to help decide whether or not to give the measured colostrum or other colostrum to the calf. On the other side a flowchart would be one technique to illustrate the steps of the entire colostrum management process and other issues involved.

SOPs provide a way to introduce existing and new employees to their field of work and uniform work steps for each task. The creation of SOPs can be a time saver in the training of new employees (Barbé et al., 2016). However, few studies have addressed the implementation of SOPs in livestock production and their consequences. There is a lack of direct comparisons between data collected before and after the implementation of SOPs. In contrast, studies that do exist tend to focus on husbandry and calf handling issues (Hesse et al., 2017), rather than on colostrum management per se. This finding is further supported by the fact that SOPs are more common in dairy farming than in calf rearing (Hesse et al., 2017; Mahendran et al., 2022).

For instance, Hesse et al. (2017) surveyed labor processes on German dairy farms. Of the respondents (n = 248), 82.0% reported that SOPs generally exist. SOPs were more commonly formulated on medium (101 cows to 500 cows) and large (> 500 cows) farms. 64.0% of the respondents reported having SOPs for handling calves, with medium and large farms more likely to have SOPs. When comparing feeding and milking cows with handling calves, the percentage of implemented SOPs was higher for the feeding and milking processes (73.0%). Nonetheless, only 54.0% of the farms assessed had written SOPs, regardless of the work area. Moreover, medium and large farms were more likely to have written SOPs than small farms (< 100 cows). A correlation was found between the presence of documented SOPs and a lower first-service conception rate (52.23 ± 2.2 vs. 45.01 ± 1.8; P = 0.012) and a higher annual milk yield (9,477.2 ± 119.7 kg vs. 9,827.9 ± 103.8 kg; P = 0.028). Farmers mainly expected three benefits from the implementation of SOPs: consistent work performance (86.0%), monitoring of work processes (49.0%), and improved animal health (39.0%) (Hesse et al., 2017). These three points, in particular, could be achieved through the use of SOPs in calf management and especially in colostrum management. In a survey conducted by Neukirchner et al. (2024) German farmers were asked regarding the utilization of written SOPs in calf rearing. The results indicated that, on average, only 13.1% of respondents (n = 1,230) had written SOPs for different tasks. Conversely, 69.4% of respondents expressed a desire for written SOPs for specific tasks (n = 995). Notably, 70.1% of respondents indicated a preference for SOPs pertaining to colostrum quality (n = 101). Only 11.5% of the farms had an SOP in place that specified how to access colostrum quality. This number indicates a lack of SOPs in the area of colostrum management, suggesting potential for improvement.

Communication with external advisors (e.g., veterinarians) can help to develop SOPs (Stup, 2017), but large farms are also more likely than small farms to seek external advice (CI = 0.22–0.81; P = 0.013) (Hesse et al., 2017). Due to their differentiated perspectives, contact with other farmers and foundational knowledge, the expertise of external supporters should be considered when implementing changes to management practices. In their survey, Mills et al. (2020) investigated the impact of improvement ideas from different advisors, such as veterinarians and scientists, on the development of SOPs. Five areas emerged when implementing external advice: (1) implementability of the advice, (2) resources required, (3) priority of the advice, (4) other stakeholders involved, and (5) importance of data. These five factors must be considered from both an internal and external perspective in the implementation of external consulting.

Atkinson et al. (2017) investigated the effect of benchmarking on FPT in rearing calves. The results suggested that routine measurement of Ig in the Plasma for the recording of TPI or FPT should be incorporated into work protocols and instructions to detect errors in colostrum management. However, the German legal situation regarding the routine measurement of Ig in the Plasma by farmers is unclear. According to the Animal Welfare Act, any intervention involving pain on a vertebrate animal without anesthesia is prohibited (BMJ, 1972) and diagnostics are commonly the privilege of veterinarians. Since a blood sample is required to measure the plasma Ig concentration used to determine TPI or FPT, it must first be clarified whether this is legally permissible for the farmer. Prior to the study of Atkinson et al. (2017), none of the participating farms determined colostrum quality and the rate of FPT. Eight of the 18 farms generally used frozen colostrum reserves. After benchmarking, five of the farms implemented colostrum-specific management changes. Most farms increased the amount of colostrum fed to deliver sufficient amounts of Igs. In addition, they also shortened the interval between the first milking and feeding or invested in colostrometers and refractometers to evaluate the colostrum quality. Both the timing of the first feeding after birth and the amount of Ig given to the calf are critical influencing factors. Delayed feeding can affect colostrum quality. Therefore, these are good approaches for improving colostrum management (Study 1). Furthermore, farms modified the way they stored colostrum (Atkinson et al., 2017). As shown in Study 2, storing colostrum is an important starting point as there is a lot of potential for improvement in colostrum management. Freezing and thawing of colostrum can affect the Ig concentration depending on the procedure. Careful handling and correct storage are therefore important. It is clear that few standards are defined in the area of colostrum storage and that different practices are used and not all practices are positive for colostrum management (e.g., too low temperature during freezing, too high temperature during the thawing process). Atkinson et al. (2017) demonstrated that these changes resulted in a lower incidence of

FPT. Eleven farms made colostrum-related changes; their mean value for FPT before the changes was 21 ± 10%. After the changes, this value decreased to 11 ± 10% (Atkinson et al., 2017). Further studies should specifically investigate the influence of SOPs on animal health. In a case study from Great Britain, colostrum management was improved to reduce the high sterility on a farm (Mason, 2012). Measurements showed that only one in ten calves had sufficient TPI. During the improvement, SOPs were adapted, the measurement of colostrum quality was implemented, and hygiene aspects were improved. Beyond that, colostrum was stored at −20°C instead of room temperature. Significant improvements were noted over time, with only four out of ten calves failing to achieve adequate TPI. Moreover, the mortality rate dropped from 9.0% to 3.0%, and the rate of calves with scours, pneumonia, or navel illness in the first-month p.p. dropped from 60.0% to 30.0% (Mason, 2012). The study's findings indicated that the impact on colostrum is not only due to changes in quality but also to the management of freezing. Colostrum should be fed or frozen as soon as possible after milking, as storage at room temperature contributes to faster bacterial growth (Stewart et al., 2005; Johnson et al., 2007; Godden et al., 2019). According to Study 2, the majority of respondents froze colostrum at a temperature rang from −10°C to −19°C. The effect of temperatures in the range of −10°C to −19°C on TPI and disease rates after feeding frozen colostrum should be further investigated because the temperature at which colostrum is frozen affects the composition of the colostrum (Godden et al., 2019). A change in the composition of the colostrum is very likely to affect the absorption of Ig, which in turn leads to a change in the TPI. In order to prevent FPT with optimal storage management, it is therefore crucial to be aware of the potential effects. If research shows that colostrum frozen at a temperature lower than −19°C has a more positive effect on TPI and calf health than colostrum frozen at higher temperatures it is important to communicate this information to advisors and farmers. As indicated in Study 2, the data pertaining to the storage period for colostrum at a temperature of −20°C exhibits a considerable degree of variability, ranging from a period of three months to one year (Abd El-Fattah et al., 2014; Hopper, 2021). Further research is therefore required to determine the optimal method and duration for freezing colostrum. The results of these studies must then also be disseminated to farmers.

In principle, the growth of bacteria in colostrum should be kept as low as possible and SOPs should be established for the optimum procedure to achieve this goal. In the case of sick cows, it is advisable to utilize reserves or fresh alternatives. However, if there is no alternative to feed, it is preferable to feeding no colostrum at all. An increased presence of bacteria in colostrum fed to calves can also be linked to inadequate preparation of the udder prior to milking and contamination of feeding equipment. This includes, for example, equipment used to collect the milk and store or feed the colostrum (Hyde et al., 2020; Fecteau et al., 2002). If the equipment is not cleaned thoroughly, it is susceptible to the formation of milk deposits. Such residues can serve as a breeding ground for bacterial growth, which may result in contamination and deterioration of the equipment (Teh, 2015). Before milking, the udder should be cleaned and milked into a very clean and dry can. Other equipment should also be cleaned regularly and intensively (Geiger, 2020). In their respective studies, Chancy et al. (2023) and Renaud et al. (2017) demonstrated that almost every feeding equipment tested was contaminated. Buckets and teats were the two most frequently contaminated pieces of equipment. Additionally, the inside of the teat, in particular, can be highly contaminated (Renaud et al., 2017; Heinemann et al., 2021). Teats can be challenging to dismantle and some areas are difficult to reach when cleaning. In contrast, buckets have a large opening, which can facilitate contamination due to the influence of the environment and frequent use (Chancy et al., 2023). In their study, Heinemann et al. (2021) demonstrated that none of the elven farms visited, used a standardized cleaning protocol. Additionally, significant variations were observed in the cleaning intervals and methods between the different farms. These findings suggested that there is no uniform approach to cleaning feeding equipment adequately and that the optimal cleaning procedure remains uncertain.

In an Australian study (n = 240), 28.0% of colostrum samples had a TPC of 10,000 cfu mL^{-1} to 100,000 cfu mL^{-1}, and 42.0% had a TPC > 100,000 cfu mL^{-1}. TCC was between 1,000 cfu mL^{-1} and 10,000 cfu mL^{-1} in 5.0% of the samples, and 6.0% had a value > 10,000 cfu mL^{-1}. There was no bacterial growth in only 63.0% of cases (Phipps et al., 2016). Abuelo et al. (2019) recorded the percentage of farms in Australia that met the limits for TCC and TPC. The targets for TPC were met by 58.4% and for TCC by 72.4%. However, only 19.5% of the farms could meet the criteria for TCC and TPC and simultaneously achieved an IgG concentration > 50.0 mg mL^{-1} in colostrum. In Phipps et al. (2016), this value was slightly higher at 23.0%, and in an American study, almost twice as high at 39.4% (Morrill et al., 2012). High levels of TPC and TCC exceeding the thresholds were also found on Irish farms (n = 214, TPC = 56.5%, TCC = 32.7%) (McAloon et al., 2016). These values showed that the range of bacterial growth in colostrum needs to be optimized. Clear instructions for cleaning udders and materials (e.g., under what circumstances, how often, which cleaning agent) could lead to improvements and would be good to define in SOPs.

SOPs can be an effective tool for all areas of farm management; however, SOPs should not be used as the sole source of information for employees. To create SOPs specifically for colostrum management, farmers can use existing SOPs from the Internet (e.g., Centre for Dairy Education and Research, 2020) or Macdonald Campus Farm Cattle Complex, 2023) and also use the 5 Q's as a starting point. However, the individual management aspects of the farm must always be considered so that adjustments can be made. Employees need to understand the entire process behind a SOP to ensure a smooth operation that promotes animal welfare. Inaccurate information supports the negative aspects (Schuenemann et al., 2013). For instance, the assessment of colostrum quality frequently relies on a visual evaluation. While characteristics such as viscosity and color can provide initial indications of quality, they are not sufficiently precise for a reliable assessment (Study 1). Nevertheless, there is a widespread perception that a visual assessment is sufficient.

The meaning of information and understanding the importance of that information around improving (colostrum) management on farms are directly related to animal welfare. A lack of information can slow down management adjustments or lead to a misperception of the situation, resulting in negative consequences for animal welfare. Nevertheless, the data on the effects of implementing SOPs in colostrum management on calf health remains insufficient. However, it can be assumed that the standardization of processes will result in a reduction in the number of errors and instances of work being overlooked (Nissinboim and Naveh, 2018; Amare, 2012). These measures enhance the quality of work, and in the case of calf husbandry, they improve animal welfare and health (Mason, 2012).

5.2 Knowledge Transfer for Better Colostrum Management

Effective colostrum management, including SOPs, requires target group-specific knowledge transfer. Without this transfer, it is impossible to develop and implement good colostrum management practices. Knowledge transfer is essential for implementing best practices and scientific recommendations. According to our survey (Study 2), while most farmers recognize the significance of good colostrum management, they may not always be aware of the recommended practices. These recommendations cover not only general aspects, such as measuring the Ig concentration in colostrum, but also specific points, such as the optimal temperature, quantity, and container for freezing colostrum reserves. In addition, farmers should be trained to understand the various factors that influence colostrum quality, as outlined in Study 1, and to take appropriate measures to promote calf health. The results of our survey indicated that the colostrum of cows in their first lactation is still being fed without undergoing testing for Ig concentration. This contradicts the literature, which showed that the Ig concentration in the colostrum of these cows can be significantly lower than the concentration in the colostrum of older cows (Study 1).

Knowledge transfer can also contribute to the creation and implementation of SOPs. Hesse et al. (2017) clarified that 98% of the surveyed farmers perceived the potential for optimization on their farms, but lacked both knowledge (42.0%) and the time (41%) to formulate defined SOPs. In addition to knowledge, having sufficient time to prepare the SOPs is an important factor to consider. As shown in Study 2, farmers and employees are often involved in a variety of tasks and are not focused on one area of responsibility. As a result, there is often no time for SOP development. This aspect is also confirmed by a Canadian study, which found that farmers tend to put off writing SOPs when other work, such as harvesting, needs to be done (Mills et al., 2020). However, changes related to calf management must be approved by the farmer, who is responsible for all animals on the farm. Therefore, the farmer must be committed and motivated to work towards improvements whenever calf management is altered (Sumner et al., 2020), despite time restrictions. For instance, a relationship has been discovered between the time required to treat cow lameness and the perspectives, priorities, and emotional reactions of farmers. The farmer's values can influence the handling of specific situations, such as animal welfare and health aspects (Horseman et al., 2014). The study by Koralesky et al. (2021) found that participants viewed colostrum management as a routine task, which influenced the implementation of changes. The authors suggested that targeted interventions or on-farm presentations should demonstrate tasks such as milking, time management, freezing, and tools for testing colostrum quality, including the colostrometer and refractometer, to improve colostrum management. Studies that examined interventions on dairy farms indicated that implementers should engage in active discussions with employees and managers. Additionally, it is recommended to establish farm-specific goals in collaboration with farmers and employees (Koralesky et al., 2021).

Farmers have always had to adapt to changes, but now the changes and resulting adaptations are more complex and better understood. To successfully embrace these changes, it is necessary to have information, knowledge, and a willingness to learn (Münchhausen and Häring, 2012). Worldwide, various measures are being taken to improve the health and welfare of cattle and their offspring's, including research projects and herd health and extension programs. It is insufficient to only generate knowledge; farmers must actively participate in the processes as key players, and the knowledge must be deliberately imparted to them. While much knowledge exists in science to prevent or treat diseases and ailments, ongoing usage and coordination of the comprehensive system are required for prevention. It is crucial to translate scientific features into practice. This can be achieved by integrating the knowledge into on-farm applications or through specific practical implementations. Nevertheless, farmers need to be motivated to implement changes. Training courses can provide an opportunity to deepen knowledge, but they can also contribute to motivation and confidence. A German study showed that farmers had low confidence in measuring Ig concentration to quantify colostrum quality before attending a training course. After attending a step-by-step training course, confidence levels increased significantly. Before the course, 31% of participants indicated a lack of confidence in their ability to complete the task. 50% said they were confident. Following the course, the percentage of participants who lacked confidence in their ability to complete the task decreased to 4.0%, while the percentage of participants who expressed confidence increased to 77.0% (Neukirchner et al., 2024).

Close collaboration between farmers and external advisors is essential for implementing farm-specific solutions (Lam et al., 2009). Knowledge transfer must be customized to different farmer groups, as their willingness to interact with outsiders varies. In their study, Jansen et al. (2010) categorized participants into four groups: proactivists, do-it-yourselfers, wait-and-see-ers, and reclusive traditionalists. Each group had a unique approach for handling external advice or, in some cases, did not want to receive advice at all. The objective should be to provide all groups with relevant information through tailored knowledge transfer. To achieve this goal, it is necessary to develop specific concepts to engage farmers who are not actively participating in training courses or are resistant to external advice. The sources of information are crucial in this regard, as they vary significantly among farmers (e.g., journals, presentations, other farmers) (Jansen et al., 2010).

External advisors, particularly veterinarians, play an important role in knowledge transfer. Sumner et al. (2020) found that benchmarking enables veterinarians to demonstrate their expertise. In their study, veterinarians were consulted on calf management, and benchmarking improved farmer-veterinarian interactions. Prior to receiving benchmark reports, veterinarians were mainly called for treatments and solely viewed as a source of information for disease and pain management. Afterward, farmers significantly trusted veterinarians' knowledge of colostrum management. Trust in veterinarians is based on their experience and knowledge gained from working on other farms. Veterinarians are, therefore, vectors for the rapid and widespread transfer of knowledge. Direct discussions between veterinarians and farmers motivated the farmers to strive for management changes and helped them understand the information (Sumner et al., 2020). Veterinarians can provide advice on how to improve farm-specific colostrum management and identify areas where changes need to be made based on this trust. Additionally, SOPs for these areas could be developed with the veterinarian to improve management and animal welfare. Veterinarians are required to participate in ongoing educational programs to ensure that they remain informed about the latest developments in their field. The insights gained from these programs can then be shared with farmers, who are not required to attend similar training courses on a regular basis. However, a Dutch study found that only 10.0% of veterinarians provided structured advice to farmers. This advice included pre-programmed protocols without clinical treatment (Boersema et al., 2013), which would include SOPs.

Benchmarking can lead to changes, particularly when farmers are motivated to solve specific problems. Targeted competition can also be used to encourage improvement by comparing it with other farms (Wilson et al., 2023). However, Wilson et al. (2023) showed that limited resources can be a barrier to motivation. Additionally, hands-on farmers, do-it-yourselfers and wait-and-seers may have less motivation through benchmarking. Proposals and specifications for targeted changes from external sources should, therefore, always be discussed and made in the context of economic operating data and limited resources.

As an executing component, the human being plays an essential part in the implementation of new practices. The executing person must be allowed to practice new techniques and acquire confidence in their abilities. It is important to practice in a familiar environment and below the existing influencing factors of the respective farm (Schuenemann et al., 2013). Schuenemann et al. (2013) evaluated a course on the proper procedure for calving cows. Based on the evaluation, the course effectively increased the participants' knowledge level, imparted relevant information applicable in practical settings, and motivated them to follow best practices. A study conducted in New Zealand found that 66.0% of farmers who attended two educational events reported making or planning to make changes based on the presented knowledge (Dodunski, 2014). In Germany, 80% of participants found events such as workshops and field days to be helpful, with 65.0% preferring half-day workshops. Furthermore, 70.0% expressed interest in international comparisons (Münchhausen and Häring, 2012). Knowledge transfer events are highly favored by farmers as they aid in the critical analysis of work and management processes. Therefore, it is recommended that aspects related to colostrum management be addressed more frequently in such events. Training courses on measuring Ig concentration in colostrum can be combined with information on freezing colostrum reserves and the appropriate thawing process.

5.3 Importance of Data for Better Colostrum Management

In recent years, the importance of data and data management has increased, along with the significance of SOPs and knowledge transfer. Calf management is a complex process that generates data, including through colostrum management. It is crucial to consider the various factors that influence this process. Colostrum management not only affects the calf but also its development into an adult cow. Therefore, farmers should include animal-specific colostrum data, such as Ig concentration, the quantity of fed colostrum, and TPI information. Improvements in data management can help to optimize colostrum management practices and achieve better results in calf rearing (Study 1). In a study by Faber et al. (2005), the effect of colostrum feeding on growth, development and milk yield until lactation was investigated. The study found that calves fed 4 L of colostrum gained up to 0.23 kg more milk per day than those fed 2 L. These findings demonstrated that cow longevity is affected by sufficient colostrum consumption. Although the milk yield of both groups was similar in the first lactation, there was a significant difference ($P < 0.05$) in the second lactation. Cows in the 4 L colostrum group produced 1,349 kg more milk than those in the 2 L colostrum group. The results are supported by Sutter et al. (2023) and Tautenhahn et al. (2020). Therefore, colostrum management data, including quantity, quality, and quantification, also play a crucial role in the adult cow. Drawing conclusions about the reasons for high disease rates and low milk quantity in cows based on colostrum management data is possible.

Few farmers recognize the economic importance of colostrum management, according to a study by Palczynski´s (2021). The authors attributed this to a lack of monitoring data on calves. They concluded that this lack of data is the reason colostrum management is not given enough weight as a preventive intervention against high calf mortality. Consequently, additional data, especially on mortality rates, would strengthen the importance of adequate colostrum management and highlight its economic implications. Economic considerations are one of the seven primary factors that can prompt modifications in farmer behavior and process adaptation (Rose et al., 2018). This would provide an approach to argue for adjustments, as these bring economic benefits.

Sumner et al. (2018) found that most farmers considered data inclusion important, regardless of the outcome. However, some farmers did not use the additional information for decision-making, despite believing it to be beneficial. Others found that data recording helped identify management patterns. A survey conducted by Palczynski et al. (2020), revealed that farmers rarely kept track of disease outbreaks or mortality rates. The employees only recorded basic information on whiteboards or books, such as colostrum feeding or cases of diarrhea and respiratory disease. However, they did not keep long-term records of these relevant data nor statistical analytics. Instead, they mainly used it for daily communication among themselves. Nevertheless, the use of cloud-based services for calf data collection was viewed positively and recognized as a simplification of the data collection process (Palczynski et al., 2020). Farmers know the data but are not able to use it optimally. It can be assumed that they are not sufficiently aware of the inferences that can be drawn from the data. This implies that there is also a lack of knowledge transfer in this area.

Data evaluation can also serve as a motivator for employees. Sumner et al. (2018) discovered that benchmarking improved calf management by providing farmers with access to information and comparisons with other farms. Previously, farmers based their self-assessment mainly on data such as low mortality or the first calving age of calves. Even though benchmarking can be demotivating for some groups (e.g., hands-on-farmers, do-it-yourselfers) (Wilson et al., 2023), comparing data directly with other farms in a comparative context can strengthen farmers' self-confidence. However, some farmers may perceive the improvements resulting from data collection as insignificant or not worth the additional effort. This is particularly true given that data collection can be time-consuming and increase labor costs. Therefore, the benefits of data collection must outweigh these costs (Palczynski et al., 2020). Information plays an essential role in identifying management problems and facilitating subsequent improvements. Therefore, it is important to recognize its significance as part of the improvement process. A shortage of information can impede the implementation of new management measures (Sumner et al., 2018).

As a digital link between data from colostrum management and a herd management program is not yet possible, the data is currently retained in mainly written form or transferred manually, which is labor-intensive. At this point, an appeal should be made to develop cross-system data transmission. According to Mills et al. (2020), farmers who participated in the interviews reported that integrating data was advantageous, especially in terms of positive outcomes. While a significant amount of data is collected, monitored, and transformed into useful information for farmers in relation to the dairy herd, this process occurs much less frequently in calf rearing (Bach and Ahedo, 2008).

Nevertheless, there are also advancements in calf rearing. Therefore, it is crucial to determine how to integrate data on colostrum management in the long run. Study 1 demonstrated that refractometers and colostrometers provide simple ways to measure IgG concentration in colostrum before feeding, freezing, or after thawing the frozen colostrum. The digital refractometer calculates and displays concentration automatically, eliminating the need for a reading against a light source as required by the optical refractometer. However, currently, autonomous methods are lacking in measuring Ig concentration and transferring data from the colostrum measuring devices to a herd management program. Therefore, the data must be manually entered into a program for future use. A first attempt to automatically detect the Ig concentration was made by Lemberskiy-Kuzin et al. (2019). The authors recorded Ig concentration using the online Afilab spectrometer and tested its capabilities by collecting 205 colostrum samples from 72 cows. The online measurement device is based on a near-infrared signal and is intended to determine the colostrum quality in real-time. An ELISA was performed as the gold standard. The correlation coefficient between the ELISA and the online measurement device was 0.70 (6.0 mg mL^{-1} to 119.0 mg mL^{-1}). The recorded concentrations were directly stored in the associated management system (Lemberskiy-Kuzin et al., 2019). Automated measurement of Ig concentration would simplify the process and reduce working time. Simplification and reduced working time would eliminate the argument that measuring Ig concentration and saving the data increase working time (Study 2). Furthermore, the data could be automatically tracked for eac animal and retrieved as needed. It would also be beneficial to include SOPs in the digitization process. The automated measurement of the Ig concentration described above means that one step in the SOP “measurement of the Ig concentration” is verifiably completed, as the step is recorded in the herd management system. A digital proof of completed SOPs could provide a level of commitment to completing the steps. The monitoring tool needs to be simple and easy to understand and integrate with the implementation of the SOPs. This would allow for the active request of feedback on the individual steps. For each calf and its colostrum management, there would be a recorded procedure. This record can then be used not only for monitoring but also by other employees. The result of this process could be the development of a comprehensive system of SOPs and data management, which could potentially increase the value proposition for farmers, veterinarians and employees.

In addition to collecting data about Ig concentration, it is essential to quantify TPI. This parameter indicates whether there are any issues with colostrum management. If FPT occurs continuously, the colostrum management process should be monitored and examined for vulnerability (Geiger, 2020). Continuous monitoring of colostrum intake by calves with regard to the quality and quantity of colostrum should be a standard practice on dairy farms to prevent FPT. Limit values for the determination of TPI have been established and discussed in numerous studies, as mentioned in Study 1 (Elsohaby et al., 2015; Dunn et al., 2018; Sutter et al., 2020). Because the age of the calf affects the measurement of total protein concentration, it should only be performed on calves one week old or younger. Furthermore, dehydration affects the accuracy of the results (Cuttance et al., 2019). This knowledge must be passed on to farmers as part of knowledge transfer. Aghakhani et al. (2023) investigated the effect of STP concentrations at 24-h p.p. on the health and growth performance of Holstein calves. The study found that for each increase of one STP, the calf's final weight increased by 6.53 kg (CI = 3.86–7.91; $P > 0.001$), and daily gain increased by 23 g day^{-1} (CI = 16.9–26.8; $P = 0.04$). The results suggested that STP 24-h p.p. has an effect on body weight, daily gain, starter feed intake and health aspects. Consequently, regular measurement of STP 24-h p.p. should be the goal in the future in order to draw animal-specific conclusions. Data on STP levels and, thus, inferences about TPI can be used as an indicator of disease. Crannell and Abuelo (2023), found that calves with good (5.8–6.1 g dL^{-1}), fair (5.1–5.7 g dL^{-1}), and poor (< 5.1 g dL^{-1}) TPI were 14.0%, 32.0%, and 49.0% more likely to be treated for diarrheal disease ($P \leq 0.02$). Calves that received fair or poor colostrum had a 21.0% and 51.0% more likely risk of getting sick during the rearing period ($P < 0.001$). The transfer of Ig can also impact reproduction-related parameters and may be useful in reproduction management if the relevant data is tracked (Crannell and Abuelo, 2023). This information can also be utilized in a preventative manner. Calves with a low STP can be selected at an early stage and excluded from heifer rearing. Additionally, the husbandry can be optimized to specifically reduce the bacterial load for this calf, as it is known from the STP value that it is more susceptible to diseases. Palczynski (2021) stated that determining TPI, along with health, growth, and performance data, can be used as arguments to justify the increased time, labor and funding required for good colostrum management.

5.4 Conclusions

In conclusion, calf management, including efficient colostrum management, is the cornerstone of any dairy farm, yet it receives insufficient attention. This thesis combines the current status of colostrum management on German dairy farms with the existing knowledge about colostrum management, especially regarding measurement methods and influencing factors. In this way, potential improvements in colostrum management on German dairy farms can be identified, as enhanced colostrum management has a significant impact on calf development and herd performance. Colostrum management is widely recognized as important on German dairy farms, but discrepancies have been identified between scientific knowledge and its implementation on farms. It appears that farmers may not be realizing the full potential of recommended practices due to a lack of calf monitoring data and knowledge transfer. Furthermore, farmers are engaged in a number of tasks and are not only responsible for calf rearing. With limited time, it is a challenge to implement new methods and integrate them directly into farm operations. Despite the availability of methods to detect Ig concentrations in colostrum or blood serum, there are significant gaps in the implementation of these monitoring measures. The same result can also be seen for the process of colostrum storage. These results indicate that knowledge transfer and organizational practices must be improved. Benchmarking and establishing SOPs involving employees and external experts can contribute to better colostrum management and reduced incidence of FPT. Such improvements lead to reduced losses, healthier calves, and longer-living, high-performing cows. However, due to the diverse nature of dairy farms, customized solutions are necessary, considering factors such as operational goals, equipment, and management practices. In addition, scientists need to address knowledge gaps and effectively communicate available information to farmers in order to implement optimal colostrum management techniques. It is recommended to address colostrum management more frequently in training courses, and combine training on measuring Ig concentration with information on freezing and thawing colostrum reserves. Integrating colostrum data into long-term records could reinforce the importance of proper management and underscore its economic implications. However, implementation is not possible without the cooperation of farmers, so their views should be actively involved in all points. If the above issues remain unaddressed in the near future, it seems inevitable that certificates of competency will become a mandatory requirement. This would be a method of fulfilling our obligation to provide for the well-being of calves. Addressing these challenges is essential for optimizing calf rearing practices and ensuring the long-term sustainability and welfare of dairy farming.

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6 Appendix

6.1 Supplemental Material for Section 5

Standard Operating Procedure (SOP) for Measuring Ig Concentration in Bovine Colostrum Using an Optical Refractometer

Purpose

To provide farmers with a simple and effective method to measure the immunoglobulin (Ig) concentration in bovine colostrum using an optical refractometer, ensuring it is suitable for feeding newborn calves. The **threshold for good quality colostrum** is set at **22% Brix.**

Scope

This SOP applies to all farmers and farm workers who are responsible for assessing the quality of bovine colostrum used in calf rearing.

Materials and Equipment

- Optical refractometer (calibrated in % Brix)
- Distilled water
- Colostrum sample
- Dropper or pipette
- Soft tissue or lens paper
- Logbook or recording sheet

Procedure

1.1 Calibration of the Refractometer

I. Prepare the Refractometer:

- Ensure the refractometer is clean and dry.

II. Calibrate with Distilled Water:

- Place a few drops of distilled water on the prism of the refractometer.

- Close the cover plate.
- Look through the eyepiece and adjust the calibration screw until the reading is 0% Brix.
- Wipe it dry with a soft tissue or lens paper.

1.2 Sample Measurement

I. Prepare the Colostrum Sample:

- Collect a small amount of colostrum immediately after milking.
- If the colostrum is refrigerated or frozen, ensure it is well-mixed and at room temperature before testing.

II. Apply the Sample:

- Clean and dry the prism of the refractometer with a soft tissue or lens paper.
- Place 2–3 drops of colostrum on the prism using a dropper or pipette.

III. Take the Reading:

- Close the cover plate and make sure to spread the colostrum evenly.

- Align the refractometer with the light source. Look through the eyepiece and read the %Brix value directly from the scale.

IV. **Interpret the Result**:

- If the reading is 22% Brix or higher, the colostrum is considered good quality and suitable for feeding newborn calves.
- Record the reading in the logbook or recording sheet. If you freeze the colostrum, also note the %Brix value on the container for freezing

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1.3 Cleaning the Refractometer

I. **Clean the Prism**:

- Rinse the prism with distilled water.
- Wipe it dry with a soft tissue or lens paper.

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