Implementing physically effective neutral Detergent Fiber to influence ruminal Metabolism, Diet fermentability, feeding Behavior and Risk of SARA in high-producing dairy Cattle

A narrative review

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Preface

This bachelor's project was written as a conclusion to a bachelor's degree at Copenhagen University – Section of Medicine and Surgery and is written in the style of a narrative review. The review was made to investigate the potential applications and feasibility of implementing the peNDF system to influence cow responses. The length of this project is 3962 words, excluding the title face, preface, list of contents, danish resume and appendix.

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Abstract

To increase productivity on dairy farms, high percentages of energy rich grains are fed to dairy cows, possibly leading to drops in milk fat, ruminal pH and the disorder of sub-acute ruminal acidosis (SARA). To prevent this, forage to induce salivary buffering and stabilize ruminal fermentation is needed, leading to the creation of the physically effective neutral detergent fiber (peNDF) system. Increased peNDF in the diet is positively correlated to increased chewing, milk fat and ruminal pH, whereas the effect on feeding behavior, dry matter intake (DMI), milk yield and digestibility more uncertain. Because of potential drawbacks, models of peNDF adequacy should be adjusted to optimize the inclusion of physically effective fiber without incurring the negatives associated with too high peNDF. Depending on circumstances, however, cows can have an increased demand for peNDF, as it is influenced by diet content of ruminally degradable staches, DMI and lactation stage of animals. Future research in increasing the accuracy of measurements and accounting for the differences between forage types is needed for implementation of the peNDF.

Danish resumé

For at øge produktivitet på malkekvæggårde gives store mængder energirigt kraftfoder til malkekøer, hvilket kan føre til fald i mælkefedtet, vommens pH og lidelsen sub-acute ruminal acidosis (SARA). Dette nødvendiggør grovfoder som kan inducere spytbuffering og stabilizere vommens fermentation og har ført til udviklingen af physically effective neutral detergent fiber (peNDF) systemet. Forøget peNDF i foderet er associeret med øget tyggetid, mælkefedt og vom pH, men effekten på ædeadfærd, tørstof indtag, mælkeydelse og fordøjelighed er mere uvis. På grund af eventuelle bagsider ved for høj peNDF bør modeller, som bruges til at bestemme tilstrækkeligheden af foderets peNDF indhold justeres ift. at undgå disse og samtidigt optimere inklusionen af peNDF. Afhængigt at omstændigheder kan køer dog have et forøget behov for peNDF, da dette påvirkes af foderets indhold af vomnedbrydelig stivelse samt koens tørstof indtag og laktationsstadie. I fremtiden bør forskning rette sig efter at øge nøjagtigheden af peNDF målinger og redegøre for forskelle mellem typerne af grovfoder før peNDF systemet kan implementeres.

Keywords

peNDF; effective fiber; ruminal pH; SARA; milk fat; forage; ruminal mat

Introduction

As the dairy industry continuously seeks to increase productivity and optimize the economic aspects, high-yielding dairy cows are bred and fed to meet ever increasing standards of milk production (Plaizier et al., 2008). In the interest of enabling the highest level of productivity for cows, it is of great importance to know how to balance the energy rich grains, enabling milk production, with structure enriching and stabilizing forage in the total mixed ration (TMR) (Humer et al., 2018). Starches in grains and concentrates are, like fiber in forage, fermented to short chain fatty acids (SCFAs), but starches are fermented more rapidly in the rumen, potentially leading to considerable drops in the pH of rumen fluid when given in large amounts. If this suboptimal pH is allowed to persist, the syndrome of sub-acute rumen acidosis (SARA) can develop, associated with symptoms of anorexia, diarrhoea, low body score, liverabscesses, laminitis along with decreased rumen motility and milk production (Dirksen, 1985; Aschenbach et al., 2011). Roughage and fibers are required for sustaining a stable environment and minimizing the risk of SARA, which has put a focus on the individual percentages of grains and forage in the diet. (Allen, 1997). The composition of this grain and forage, however, is potentially as important as their respective ratio of TMR in influencing the cow's response to a diet (Grant, 1997; Offner et al., 2003; Beauchemin and Yang, 2005). The peNDF concept was created to understand these interactions along with how cow responses, such as feeding behavior and ruminal metabolism, feeds back into the health and milk production parameters of the cow (Mertens, 1997).

In the effort to better characterize the physical structure and chemical properties of forage fed to dairy cows, Mertens (1997) created the concept of "Physically effective neutral detergent fiber" (peNDF) by combining measures of particle size (PS) with the concentration of neutral detergent fraction (NDF), a measure of chemical fiber content (Van Soest 1994). Feed content of peNDF is determined for a given forage or total mixed ration (TMR) but can vary by method (Grant and Cotanch, 2005). The product of the structural element of peNDF, known as the physical effectiveness factor (PEF), and the NDF content of the feed results in the content of peNDF. Depending on the method used, this content is classified as $peNDF_{>1.18}$, $peNDF_{>8}$ and $peNDF_{>19}$, based on the millimeter size of the holes in the sieve(s) (Lammers et al., 1996; Mertens, 1997; Kononoff et al., 2003).

Milk fat is another important parameter of milk production related to peNDF, as a high milk fat percentage requires a balance between sufficient energy intake and feed utilization (Van Soest 1994). Milk fat is potentially also useful as a measure of optimal ruminal metabolism and SCFA synthesis, as it correlates positively with ruminal function (Mertens, 1997; Woolpert et al., 2017). Along with ruminal pH, milk fat is a focus of multiple studies on peNDF, as an optimal rumen environment is required for efficient SCFA production by microbes (Mertens, 1997; Zebeli et al., 2008). The role of peNDF in optimizing ruminal fermentation to increase milk fat, and any influence on milk yield, is therefore also a subject of interest in the review.

Lastly, feeding behavior, dry matter intake (DMI) and diet fermentability are linked through the intake limiting effects of though-to-chew and hard to digest fibers found in forage, along with filling of the rumen (Haselmann et al., 2019). Because peNDF and particle size might be detrimentally correlated with these properties, understanding when they necessitate lowering the peNDF content in the TMR, is essential to a model aiming to maximize milk production. The interactions of grains, diet digestibility and DMI with milk fat, ruminal pH, milk yield and feed utilization efficiency, create the complexities of studying peNDF and making universal models of peNDF adequacy in the diet (Zebeli et al., 2006, 2010b; Grant, 2022). In this project the goal of the review is to characterize what considerations of methods, feed characteristics and cow attributes are required to create and potentially implement peNDF as a way to influence ruminal metabolism, diet fermentability, feeding behavior and risk of SARA. Taking these considerations and discussing them in relation to practical applications of feed characterization and ration formulation systems, will likewise be a goal of the discussion.

Methods and materials

To begin the literature seach a keyword search of the title, abstract and keywords of documents in the database of SCOPUS ELSEVIER was made with the terms "physically effective fiber" AND (cow OR cattle) AND (dairy OR lactation), leading to a result of 72 papers up until 26/4/2023. After a preliminary sorting out of papers not focusing on peNDF as a way of influences animal responses, focusing on other ruminants/cattle production aspects than those subject to review and reading the abstracts to determine their applicability, the number of applicable papers was 39 papers. Additionally, to begin research on the project, I was directed to the symposium review of Grant (2022) by my instructor, which was not found as part of the literature search. Of these papers, 12 are referenced throughout this project, along with an additional 47 sources discovered through back-search of initial papers (Process outlined in appendix A). These additional sources are used to accurately credit sources of information or methods relevant in the review of peNDF.

Review

Understanding the concept

The physiological roles of peNDF content are multifaceted, owing both to chemical and physical properties, but to discuss them in greater detail it can be helpful to consider the chemical and physical properties separately before analyzing their interactions.

In chemical terms fiber is composed of mainly cellulose and hemicellulose (NDF) and non-digestible compounds (e.g. lignin) is found most abundantly in forage, while also present in grains (Van Soest 1994). These complex carbohydrates are fermented in the rumen by bacteria, fungi and protozoa to fatty acids (Aschenbach et al., 2010). The fermentation of forage doesn't represent a challenge to the pH and metabolism of the rumen microenvironment, as SCFAs are absorbed across the stratified squamos epitelium (SSE) in the rumen (Aschenbach et al., 2011). The easily degradable starches found in grains, can however be fermented to SCFAs by microbes so quickly that it can overwhelm the absorptive capabilities of the rumen when concentrates make up great proportions of the TMR (Steele et al., 2011).

The main way the physical structure of feed directly influences the cow is by increasing the time required for eating, ruminating and ruminal degradation of feed (Allen, 1997; Mertens, 1997). The physical structure of forage or TMR can be thought of in terms of mean PS, and while it isn't interchangeable with PEF, a higher mean particle size generally means a larger physical effectiveness factor (Mertens, 1997). Large particles have a smaller relative surface-area for microbial digestion than smaller particles but are passively retained in the rumen until they reach a sufficiently small size, leading to prolonged time of rumination (Allen, 1997). Since saliva of cattle contains a neutralizing buffersolution of compounds such as urea and bicarbonate, it means that a larger amount of buffersolution is introduced into the rumen the longer the cow spends chewing (Allen, 1997). Because peNDF combines the physical and chemical aspects of forage most important in determining the chewing requirement of feed, it leads to measure of the intrinsic ability of a diet to induce chewing and salivary buffering, independently measurable of the cow. As it can speak to the ability of feed to neutralize ruminal acidity through buffering, estimating the amount of peNDF adequate to offset the drop in pH caused by a given percentage of concentrates in TMRs has been a primary focus since Mertens (1997) formulated the concept. Along with its primary effect on the chewing requirements of feed, the large fibrous particles associated with increased peNDF come together in the rumen to create a ruminal mat (Clauss et al., 2011). Stratification of digesta and maintenance of this mat is largely determined by the size and density of feed particles, and thereby also diet content of peNDF (Mertens, 1997). Mat formation has been found to decrease ruminal outflow while increasing ruminal motility, rumination and mixing of digesta (Allen, 2006; Zebeli et al., 2007). This has the benefit of increasing not only fiber degradation, but also the absorption of SCFA and nutrients across the SSE by increasing blood flow and surface availability of ruminal contents (Zebeli et al., 2006; Storm et al., 2012). Conversely, the lack of this stratification of ruminal digesta indicates decreased functionality and a lack of fiber in the diet of the cow, allowing otherwise digestible medium and small particles to escape degradation in the rumen (Poppi et al., 2001). Retention of particles, whether grain or forage, positively impacts feed utilization and fiberdegradation, and is a vital part as to how peNDF helps maintain milk fat through healthy fermentation (Boddugari et al., 2001; Zebeli et al., 2006, 2012).

To determine the peNDF content of a TMR, Mertens (1997) originally sieved by shaking particles vertically and focused on the fraction of particles retained on a sieve with an aperture size of 1.18 mm., as an approximation for the largest particles being eliminated from the rumen (Poppi et al., 1985; Mertens, 1997). While vertical sieving puts a focus on $peNDF_{1.18}$ content, the Penn State Particle Seperator (PSPS) is a widely adopted on-site approach to determine peNDF from the TMR. It features a handheld series of sieves stacked ontop one another to be shaken horizontally, with differing aperture sizes depending on iteration (Lammers et al., 1996; Mertens, 1997; Kononoff et al., 2003). The PSPS has been used with the two original sieves with aperture sizes of 19 and 8 mm., along with a bottom pan, which means that the distribution of smaller particles was calculated via extrapolation (Lammers et al., 1996). A modification of the PSPS with a 1.18 mm screen has also been attempted to remove reliance on extrapolation, but as Mertens (1997) observed, horizontal sieving tends to sort particles based on their length, whereas vertical sieving sorts based on the shortest width of particles (Mertens, 1997; Kononoff et al., 2003). The use of these different methods for determining the physical characteristics of a TMR interchangeably has been a great obstruction to implementing a model of peNDF adequacy based on studies of the subject, as it calls into question the transferability of results (Grant, 2022). The handheld nature of the PSPS means that the rate of shaking and stroke length influences the reproducibility of measurements, and PSPS measurements of peNDF in as-fed TMR samples vary as much as 10% (Grant and Cotanch, 2005; Grant, 2022). To combat this uncertainty and lack of standardization, Schuling et al. (2015) demonstrated that adding a 4 mm. sieve to the PSPS could significantly increase the correlation of measurements with $peNDF_{1.18}$ content found using vertical sieving. Scientific solutions to uncertainty related to the methods of peNDF determination will inevitably play a role in increasing the viability of studies focusing on the peNDF system, but the variation of feed associated characteristics still presents a challenge even after standardization (Grant and Cotanch, 2005). Different types of forage have differing shapes and length to width ratios, processing and mixing methods influence the distribution of PS differently and even the PS of grains influence the determination of peNDF (Mertens, 1997; Heinrichs et al., 1999). This might mean that models designed to accurately determine the cow response to peNDF content, will to be dynamically adjusted for the type of forage, TMR composition or the procedures for mixing and delivery.

Challenges to modelling the adequacy of peNDF

The preferential sorting against long particles in favor of finer, more palatable particles is an issue of feeding behavior, as it can artificially increase the concentration of grains in the short term

(DeVries et al., 2005, 2007). It has been found that high levels of peNDF can exacerbate sorting, as cows are more easily able to separate overly large particles from less physically effective grains and particles (DeVries et al., 2007; Miller-Cushon and DeVries, 2017). This makes strategies to either smooth out the feed intake or decrease the ease of particle separation viable approaches to decrease the risk of SARA on the herd level (Macmillan et al., 2017; Miller-Cushon and DeVries, 2017). While this presents a drawback to feeding high amounts of peNDF, the concept of peNDF as a measure of homogeneity in the TMR could be useful in optimizing the physical effectiveness of the diet while still including harder to separate medium and small particles (Humer et al., 2018). Secondly, dry matter intake is a point of contention, as some studies relate shorter particles to an increased DMI and nutrient intake because of decreased filling of the rumen (Dado and Allen, 1995; Teimouri Yansari et al., 2004; Haselmann et al., 2019), while others find no significant difference (Yang and Beauchemin, 2006a; b, 2007a; Tafaj et al., 2007; Alamouti et al., 2009). Because of this, some hypothesize that ruminal filling isn't always the limiting factor of intake in high-yielding concentrate fed dairy cows, but $peNDF_8$ has been found to reduce DMI, even at levels too low to adequately maintain ruminal pH (Allen, 2000; Bradford and Allen, 2007; Zebeli et al., 2010a). Potential detriments to DMI, feeding behavior and milk production in relation to high peNDF levels presents the need for establishing breakpoints in models of peNDF adequacy, whereafter increases to peNDF content doesn't contribute to further increases of ruminal pH and milk fat (Zebeli et al., 2012).

Because SARA lacks clear clinical signs, the risk of SARA has been defined in terms of either mean daily ruminal pH, or as the period where ruminal pH is reduced below a suboptimal level of 5,6-6, with severity and time increasing the risk of symptoms (Keunen et al., 2002; Plaizier et al., 2008; Aschenbach et al., 2011). Along with inclusion of too little dietary fiber, high amounts of concentrate are the main risk factor sited. Not all grains are fermented equally in the rumen, however, leading to the term rumen degradable starch from grain (RDSG) being introduced (Zebeli et al., 2008). It refers to the proportion of the total amount of starch degraded and fermented directly in the reticulorumen before exiting. RDSG can vary within grain type or across different types of concentrate such as barley and corn based on their composition (Offner et al., 2003). As management practices of using additives or processing to influence the percentage of RDSG exist, accounting for RDSG, as opposed to total starch content, will likely improve predictions of peNDF adequacy (Zebeli et al., 2008). Other risk factors of SARA include the lactation stage of cows, as those in early lactation, especially primiparous cows, are more susceptible to developing SARA (Krause and Oetzel, 2006; Humer et al., 2015). The usually abrupt transition from the lower grain, close-up diet to the high concentrate milking ration after calving leaves the SSE of the rumen unable to adapt in time, exposing the ruminal wall to damage for weeks, until the absorption of SCFA increases (Dieho et al., 2016; Coon et al., 2019). Providing additional peNDF specifically to cows at an increased risk of SARA has been proposed as a possible remedy, but if this is at the expense of DMI and nutrient intake, it instead risks exposing the cow to disorders of energy deficiency and ketosis (Zebeli et al., 2012). Supplying the needs of cows of average yield or in middle- to end-lactation might not be as challenging, but meeting the demands of high-yielding cows during early-lactation highlights the difficulty in implementing the peNDF system (Zebeli et al., 2010a, 2012).

In his original paper on the concept, Mertens (1997) puts a focus on maintaining both ruminal pH to safeguard cow health and milk fat as a vital production parameter. Through analysis of contemporary studies, Mertens (1997) recommends that 22% $peNDF_{1.18}$ of ration dry matter (DM) would be sufficient to maintain a ruminal mean pH of 6.0, while only 20% would be sufficient to maintain a milk fat of 3.4%. Later work done by Zebeli et al. (2008, 2012), instead recommend a range of 30-33% to likewise maintain optimal ruminal pH and milk fat. Importantly, the difference is more so a result of a higher standard of optimal mean pH (6.16), rather than differences in the predictions made by their models. Evidently, these percentages themselves are not useful when practically formulating rations, as TMR forage type, grain type and amount and lactation-stage all influence the adequacy of peNDF in the TMR negatively or positively, as previously outlined. Rather, Zebeli et al. (2008) uses this presumably adequate amount of peNDF to maintain a mean ruminal pH of 6.16 (i.e., 31.2%), to demonstrate the inevitable failure of a model not accounting for fluctuations in daily pH (Zebeli et al., 2008, 2012). Their modelling approach simulating the probability of the pH dropping below 5.8 for too long (decided to be 5.24 h/d) when varying levels of RDSG and DMI while keeping peNDF content at 31.2%, found that this probability ranged from 0% to as high as 45% depending on RDSG and DMI. This also illustrates that adequacy of $peNDF_{1.18}$ cannot be accurately predicted even from an attribute as influential to ruminal pH as RDSG, although DMI alone wasn't enough to increase the probability above 0%. Whether an eventual model for peNDF adequacy uses $peNDF_{1.18}$ or more recently, $peNDF_{8}$ as a basis to measure peNDF content, considerations as to how the risk of SARA is defined, along with how RDSG and DMI are dynamically adjusted for, are paramount to implementation of any peNDF system (Zebeli et al., 2008, 2012; Khorrami et al., 2021).

Milk fat is valuable both as an insight into of the intermediary metabolism of the cow and a production parameter to be optimized to incentivize and increase the economic feasibility of implementing of peNDF as a system of ration formulation (Woolpert et al., 2017). The meta-analysis by Zebeli et al. (2008) demonstrated that milk fat continued to increase linearly with $peNDF_{1.18}$ even above the recommended 30-33%, but that the milk energy efficiency would decline from this point. Milk yield however, as with DMI, is negatively correlated with particle size in some studies, while no significant influence was found in others (Kononoff and Heinrichs, 2003; Teimouri Yansari et al., 2004; Yang and Beauchemin, 2006b; Alamouti et al., 2009; Haselmann et al., 2019; Li et al., 2020). The increase in milk production was explained as an increased digestibility of diet following size reduction and a subsequent increase in uniformity and DMI combining to actually NDF intake, mat formation and energy uptake (Haselmann et al., 2019; Li et al., 2020). Studies finding no difference in milk yield when peNDF was increased might instead be overestimating the apparent positive effect of peNDF on maintenance, as milk yield, as with milk fat, is subject to variation unrelated to feed or even forage. Cows in early lactation show lower sensitivity of their milk fat percentage to peNDF and non-fiber nutrients can replace the role of peNDF in maintaining milk fat (Allen, 1997; Mertens, 1997). This happens because cows in early lactation are in a negative energy balance, where mobilization of fatty acids increases proportional to their energy deficit, possibly also explaining why milk yield didn't increase in some of the studies when the mean PS was. This lack of increased milk yield can also be explained by experiment design, the short study-periods or that cows in especially early- and late-lactation periods preferentially use excess energy to rebuild body-deposits, instead of contributing to milk production (Zebeli et al., 2012; Al-trad et al., 2009). Cows in early lactation might therefore instead need a reduction in particles to increase their energy intake, but this again contradicts the previously established elevated peNDF demand to reduce the risk of SARA.

Implementation of a system

Along with peNDF, multiple other systems have been created to evaluate the interactions between physical and chemical properties of forage, usually with a basis in different cow responses. Physically adjusted neutral detergent fiber (paNDF) has more recently been developed to predict

DMI, rumination time and ruminal pH in cows (White et al., 2017a; b; Grant, 2022). Using the 19 mm sieve of the PSPS as a measure of particle size and how this interaction with forage percentage, total forage and starch, paNDF has become the preferred measure of a TMR to maintain a given ruminal pH of the Nutrient Requirement of Dairy cattle (8th ed.; NASEM 2021). As stated in the NASEM (2021), however, paNDF is not intended to be used in ration formulation, but rather for evaluation of how diet composition and particle size affect ruminal pH. PaNDF focuses on ruminal pH and therefore rumination as opposed to the total chewing response, the focus of peNDF, which determines the structure of the ruminal mat, salivary buffering along digestion and elimination dynamics of the rumen (Grant, 2022). These differences may ultimately mean that instead of just one system finding practical use, they might end up supplementing each other in the work of future ration formulation.

Even within the peNDF concept, $peNDF_{1.18}$ and $peNDF_8$ have been found to yield greater accuracy in predicting some parameters over others. The work of Zebeli et al. (2012) found that the $peNDF_{1.18}$ and $peNDF_8$ are about equal in their ability to predict ruminal pH, but not chewing time, rumination and DMI, where $peNDF_8$ was superior. The fact that these two measures of peNDF tend to be correlated explains their similarities, but their differences highlight that other assumptions made about peNDF are not always true. Two assumptions made by Mertens (1997) are that particles making up the peNDF content have equal fragility and equal ability to induce chewing, but these differing ways of classifying peNDF reveal deviations from these assumptions. Explanations might lie in the fact that cows tend to reduce particles to a uniform size closer to 8 mm upon initial eating or simply that more fragile and therefore easier to chew particles get reduced to a smaller size quicker (Grant and Ferraretto, 2018). This means that fragility might also be a property necessary to accurately model the cow response to peNDF. Even so, the consideration of chewing associated with the initial eating is an advantage unique to the peNDF system, not intrinsically included in paNDF.

Much of the work done on the subject has focused on approaches to modelling the adequacy of peNDF to maintain certain parameters such as ruminal pH and milk fat. While progress is being made in increasing the accuracy of predictions, ways to account for the influence of differences among sources of NDF on the models remain a primary goal of future research (Grant, 2022). Forage and non-forage sources of NDF differ in composition, degradability, and shape, which influences not only the measurement of peNDF, but also how effective the measure of peNDF is in stimulating a chewing response based on ease of breakdown (Van Soest, 1994; Raffrenato et al., 2019). Likewise, the influence of fragility, density, and buoyancy of feedstuffs on ruminal mat formation and rumen turnover has remained unaccounted for since Mertens (1997) formulated the concept (Grant, 2022). The peNDF system has been implemented in the Cornell Net Carbohydrate and Protein System (CNCPS), but why peNDF hasn't been further implemented in the NASEM, BSAS or even the Scandinavian NORFOR, is however still up for debate (Sniffen et al., 1992; Grant, 2022). The NASEM now uses paNDF, but its precursor (7^{th} ed; NRC 2001) cited a lack of validation, and the intense feeding regiments that necessitate ruminal stabilization via peNDF are less common in Scandinavia, possibly lowering the incentive to break from tradition (Haselmann et al., 2019). Still, as demand for organic, pasture-fed and welfare-certified milk increases, forage might continue to account for larger portions of feed in Western countries, incentivizing the ability accurately model the influence of forage on production and welfare parameters. Overcoming tradition and the mentioned issues of implementation will create numerous challenges for dairy nutritionists seeking to further spread the influence of physically effective fibers in the coming decades. If they can overcome them however, the peNDF system has the potential to provide benefits to cow health and milk production in countries around the world, whether their primary objective is to feed millions or satisfy an increasingly demanding consumer marked.

Conclusion

Implementation of the peNDF system has the potential to predict the ability of feed to influence ruminal pH and milk fat. To model the adequacy of peNDF more precisely in the diet of cattle, models will have to account for not only intrinsic diet properties such as forage type and degradability of starches, but also lactation-stage of the cow. Along with the many dynamic influences on the adequacy of peNDF, the need for models to also make conservative recommendations, is highlighted by the potentially detrimental effects of peNDF on feeding behavior, DMI and milk yield found in literature. While these minute optimizations of peNDF content and considerations of synergy with other models might not be necessary to satisfy cows of average yield, continued optimizations and discoveries are required to meet the demands of high-producing dairy cows.

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Appendix A

1. Literature search of the title, abstract and keywords of documents in the database of SCOPUS ELSEVIER which words “physically effective fiber” AND (cow OR cattle) AND (dairy OR lactation)
    1.1. Identification result: 72 documents
2. Selection for relevance to subject based on initial reading
    2.1. Screening result: 39 documents
3. Writing of the review avoiding overlapping sources
    3.1. Inclusion of literature search:
        (Beauchemin and Yang, 2005; Yang and Beauchemin, 2006b; c, 2007b; Zebeli et al., 2006, 2012; DeVries et al., 2007; White et al., 2017a; Woolpert et al., 2017; Humer et al., 2018; Coon et al., 2019; Li et al., 2020), 11 documents
    3.2. From Volker Krömker: (Grant, 2022)
4. References found through back-searching of documents:

From Mertens, 1997:

(Poppi et al., 1985)

From Zebeli et al., 2008:

(Dado and Allen, 1995; Bauman and Griinari, 2001; Bradford and Allen, 2007)

From Zebeli et al., 2012:

(Dirksen, 1985; Lammers et al., 1996; Mertens, 1997; Heinrichs et al., 1999; Boddugari et al., 2001; NRC, 2001; Poppi et al., 2001; Keunen et al., 2002; Kononoff et al., 2003; Offner et al., 2003; Teimouri Yansari et al., 2004; Allen, 2006; Tafaj et al., 2007; Zebeli et al., 2007, 2008, 2010a; Alamouti et al., 2009; Al-Trad et al., 2009; Aschenbach et al., 2010, 2011; Clauss et al., 2011)

From Humer et al., 2018:

(Allen, 1997; DeVries et al., 2005; Krause and Oetzel, 2006; Plaizier et al., 2008; Steele et al., 2011; Storm et al., 2012; Humer et al., 2015; Dieho et al., 2016; Macmillan et al., 2017; Miller-Cushon and DeVries, 2017)

From Khorrami et al., 2021:

(Haselmann et al., 2019)

From Grant, 2022:

(Sniffen et al., 1992; Van Soest, 1994; Grant, 1997; Grant and Cotanch, 2005; Zebeli et al., 2010b; Schuling et al., 2015; White et al., 2017a; Grant and Ferraretto, 2018; Raffrenato et al., 2019; Khorrami et al., 2021; NASEM, 2021)

This adds up to a total of 59 sources