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REVIEW

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Possibilities of improving fatty acid composition of bovine milk from human health standpoint: a review

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ABSTRACT

Bovine milk fat composition is substantially different from the proposed ideal milk fat composition regarding human health. The present paper discusses the current state of knowledge on various factors affecting bovine milk fat composition and proposes possible ways of altering milk fat profile in a desirable direction. Among the physiological factors, the stage of lactation seems to have a stronger impact on milk fat composition, probably due to varying energy balance across the lactation in dairy cows. Parity and age at calving may not significantly affect milk fat composition. Milk fat composition can be altered by changes in the feeding and/or production system, although change through forages seems to be less optimistic, and change by concentrate or dietary fat appears to be costly. Genetic selection, being permanent, cumulative, and multiplicative, for better milk fat composition may result in increased proportions of more desirable monounsaturated and polyunsaturated fatty acids and decreased proportions of less desirable saturated fatty acids in bovine milk fat. It is important for dairy farmers, nutritionists, and geneticists to consider the health aspects of milk and other dairy products while making any breeding and other management decisions.

KEYWORDS

Milk fat composition; Improvement; Dairy cattle; Genetics

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Introduction

Bovine milk and other dairy products are an important part of the human diet and provide protein, fat, carbohydrates, calcium, potassium, and vitamins. Recently, there has been a growing interest in improving the health aspects of bovine milk and dairy products. According to the recommendations of the American Dietetic Association (ADA) and Dietitians of Canada (DC), 20 to 30% of energy for humans should come from dietary fat [1]. They have suggested reducing saturated and trans fatty acids in the human diet due to their role in the development of cardiovascular disease risk. Since the approach to achieve these fatty acid targets was based on food, they also suggested using low-fat dairy products [1]. The consumption of bovine milk with a high fat percentage has decreased during the past decade in most parts of the developed world. One of the main reasons for declining milk usage, at least partially, is the negative health image of the fat composition of bovine milk. Saturated fatty acids in bovine milk [mainly C14:0 and C16:0] are associated with increased levels of cholesterol and an increased risk of cardiovascular diseases [2-4]. Heart diseases are common in Pakistan, as in the rest of the world, and men and women have been shown to be at equal risk [5].

The negative health image of milk fat can be improved through changes in the production system [6,7] and/or via genetic selection [8-10]. The objective of the present review was to provide updated evidence on genetic and non-genetic factors affecting milk fat composition and strategies to improve milk fatty acid profile in a desirable direction from a human health standpoint.

Typical *Vs.* Ideal Milk Fat Composition

The fatty acid composition of bovine milk is substantially different from the proposed ideal fatty acid composition of milk from a human health point of view [11] (Figure 1). Bovine milk contains large proportions of saturated fatty acids [SFA], mainly medium-chain fatty acids [C14:0 and C16:0], while unsaturated fatty acids are in small amounts [12]. The medium chain fatty acid C14:0 and C16:0 have a role in increasing blood cholesterol levels, which negatively affects human health [3]. The unsaturated fatty acids [e.g., C18:0 or higher] are commonly considered to have neutral or positive effects on human health [13].

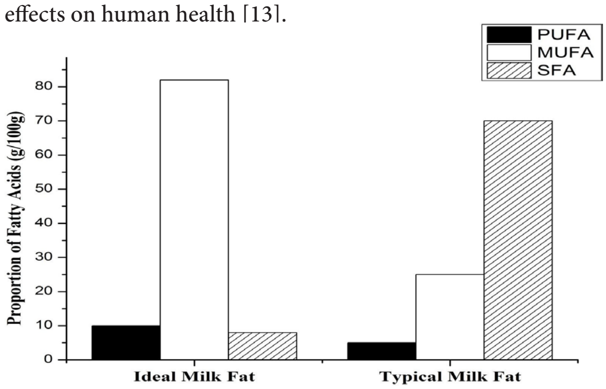

Figure 1. Typical *vs.* ideal fatty acid profile for dairy bovine milk suggested by Wisconsin Milk Board 1988 Milk Fat Roundtable [11]. **Note.** PUFA: polyunsaturated fatty acids; MUFA: monounsaturated fatty acids; SFA: saturated fatty acids.

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Fatty Acids and Human Health

Despite having potential health benefits due to calcium content, vitamin D, conjugated linoleic acid, sphingolipids, butyric acid, and fermentation products [14], the consumption of milk and other dairy products may contribute to an increased risk of cancer due to its higher saturated fat content [15]. About 70% of bovine milk fat consists of saturated fatty acids. Recent studies have suggested that only specific saturated fatty acids present in milk fat could have negative effects on human health, while other saturated fatty acids may have a neutral or even positive role [16]. Lauric acid [C12:0], myristic acid [C14:0], and palmitic acid [C16:0] have been reported to increase low-density lipoprotein [LDL] cholesterol [or bad cholesterol] in blood [3,13]. As a consequence of increased blood cholesterol levels, cholesterol builds up in the walls of arteries and gradually makes them harder and narrower. This situation may lead to eventual blockage of arteries and may result in coronary heart disease [CHD]. On the other hand, C18:0 and short chain saturated fatty acids have very little or no negative effect on human health [14]. Butyric acid [C4:0], a short chain saturated fatty acid, has been shown to reduce the risk of human colon cancer by regulating host gene expression involved in intestinal homeostasis [17].

Some unsaturated fatty acids are considered functional food as they provide additional health benefits. According to Health Canada, "a functional food is similar in appearance to, or may be a conventional food, is consumed as part of a usual diet, and is demonstrated to have physiological benefits and/or reduce the risk of chronic disease beyond basic nutritional functions." Bovine milk fat is a potential source of functional food components. Oleic acid, rumenic acid, and very long chain omega-3 fatty acids are functional foods in bovine milk fat [18]. Oleic acid, which is a monounsaturated fatty acid present in the highest concentration in milk fat (20 to 25%), is positively related to health. Diets high in oleic acid may decrease plasma cholesterol and LDL cholesterol concentrations [19]. The risk of CHD could be decreased by replacing the saturated fatty acids in the diet with cis- unsaturated fatty acids [13].

Bovine milk fat has low concentrations of polyunsaturated fatty acids (about 3-5%). A number of specific polyunsaturated fatty acids, particularly the omega-3 fatty acids and isomers of conjugated linoleic acid (CLA, cis-9 trans-11), have been positively associated with human health. Eicosapentaenoic acid (C20:5n3, EPA), an omega-3 polyunsaturated fatty acid in milk fat, has been found to potentially reduce the risk of cardiovascular diseases and inhibit tumor genesis [16]. CLA may have an inhibitory effect on the proliferation of colorectal, breast, and skin tumor cells in the studies of cell lines [20]. CLA has been shown to reduce the total plasma cholesterol concentration in humans [21].

The consumption of diets rich in trans fatty acids is associated with an increased risk of cardiovascular disease. This is because trans fatty acids increase LDL and decrease HDL cholesterol levels in the blood [13]. On the contrary, consuming a diet low in trans fatty acids may lower LDL cholesterol levels and thus decrease the risk for cardiovascular disease. Bovine milk fat contains approximately 2.7% trans-fat [12]. Trans vaccenic acid is a major trans fatty acid in ruminant milk fat. Its role as a precursor of CLA-cis-9 trans-11 is well known. However, the relationship of vaccenic acid in ruminant fat with cardiovascular disease and cancer is still not clear [22]. From the fatty acid-human health relationship standpoint, bovine milk fat has relatively high proportions of undesirable saturated fatty acids and relatively low proportions of desirable mono and polyunsaturated fatty acids.

Consumption Trends of Bovine Milk [Canada as an example]

The dietary habits of people are changing concerning milk and other dairy products. During the past twenty years, there has been a decreasing trend of bovine milk consumption with a high fat percentage in Canada. The per capita consumption of fluid milk with 3.25% fat (whole milk) decreased from 21.94 liters in 1990 to 10.46 liters in 2011. Similarly, the consumption of 2% fat milk decreased from 56.97 liters in 1990 to 36.32 liters in 2011. On the other hand, per capita consumption of 1% fat milk increased from 5.85 liters in 1990 to 17.34 liters in 2011, and consumption of skim milk also increased from 6.33 liters in 1990 to 8.22 liters in 2011. The consumption of other dairy products also changed during the last twenty years in Canada. The per capita consumption of ice cream decreased from 10.51 liters in 1992 to 4.64 liters in 2011. In contrast, the per capita consumption of yogurt increased from 2.91 liters to 8.47 liters during the same period. The per capita consumption of cheese and butter remained relatively constant during 1992-2011 [23]. The trend may not be very different in other parts of the world, especially America and Europe. This shift in consumption trend could be partially explained by the potentially negative health image of the fatty acid composition of dairy products.

Fatty Acid Synthesis in Bovine Milk

A good understanding of mechanisms involved in the biosynthesis of milk fatty acids is required to improve its content in dairy cows. Bovine milk contains 3.5 to 5% fat [18]. Milk fat is comprised of roughly 98% triglycerides [24]. In dairy cows, dietary fat is mostly in the form of C16:0 and long chain fatty acids [C18:0, C18:1, C18:2, C18:3]. These dietary fatty acids are biohydrogenated or saturated in the rumen to produce mostly C16:0 and C18:0 and also smaller amounts of C18:1 (including trans vaccenic acid), C18:2 (including CLA), and C18:3 (Figure 2). Fatty acids in milk triglycerides have two main origins. Firstly, the biosynthesis of almost all fatty acids (C4:0 to C14:0) and about half of C16:0 takes place in the mammary epithelial, and half of C16:0 and all of C18 fatty acids are derived from digestion and absorption of dietary fat and from the mobilization of adipose fat tissues [25]. Cells produce acetate and β-hydroxybutyrate during fermentation in the rumen. These fatty acids are called de novo synthesized fatty acids. The stepwise addition of acetate to β-hydroxybutyrate in the mammary gland results in the synthesis of various short chain fatty acids.

Acetate is used both as an energy source and for the biosynthesis of short chain fatty acids in the mammary gland. Secondly, about half of C16:0 and all of C18 fatty acids are derived from digestion and absorption of dietary fat and from the mobilization of adipose fat tissues [25]. Some odd chain saturated fatty acids, such as C15:0 and C17:0, are synthesized by microbes in the rumen [14].

Unsaturated fatty acids have a different synthesis pathway. Oleic acid [C18:1, cis-9], which is a predominant monounsaturated fatty acid in bovine milk fat, is synthesized

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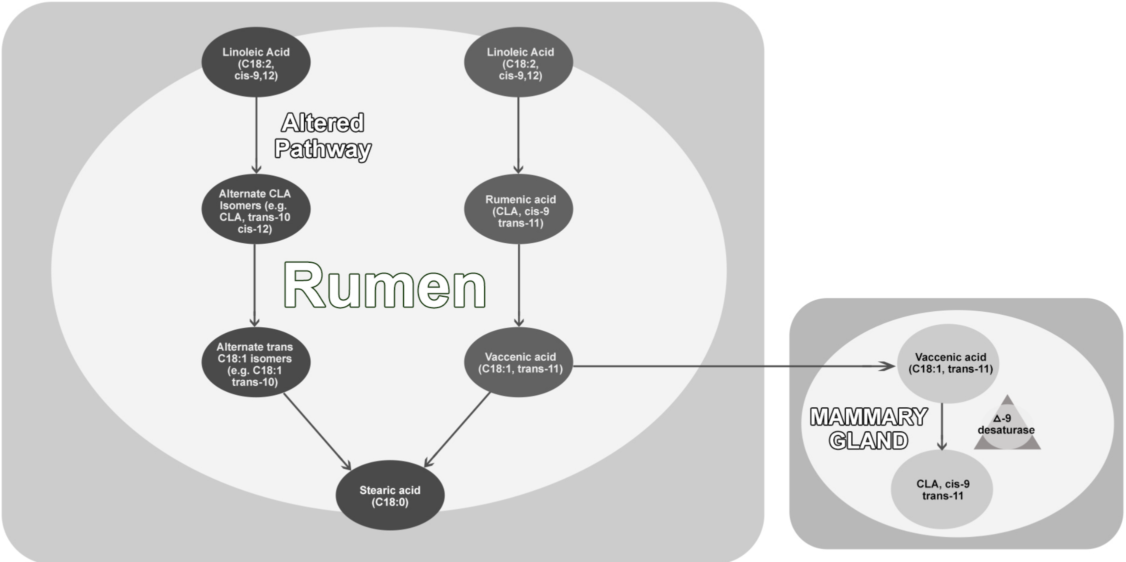

Figure 2. Rumen biohydrogenation of linoleic acid and CLA under normal and altered ruminal fermentation and synthesis of CLA in mammary gland of dairy cows [36].

mainly by the mammary uptake of C18:0 produced during rumen biohydrogenation and its subsequent conversion to oleic acid by the action of Δ-9 desaturase enzyme. However, a very small amount of oleic acid is produced during biohydrogenation in rumen [18]. Myristoleic acid [C14:1, cis- 9] and Palmitoleic acid [C16:1, cis-9] are also produced from C14:0 and C16:0, respectively, by the enzymatic activity of Δ-9 desaturase in the mammary gland. A major portion of CLA, cis-9 trans-11 in bovine milk fat is produced by a pathway similar to oleic acid; however, its substrate is trans vaccenic acid [C18:1, trans-11] (Figure 2), which is produced as an intermediate during rumen biohydrogenation [26]. The remaining portion of CLA, cis-9 trans-11 is produced from linoleic acid during rumen biohydrogenation.

Milk fat also contains 2 to 4% trans fatty acids. Trans fatty acids are either mono or polyunsaturated fatty acids. The predominant trans fatty acid in bovine milk fat is trans vaccenic acid [27]. Other trans fatty acids in bovine milk fat include elaidic acid [C18:1, trans-9], linolelaidic [C18:2, trans-9,12], C14:1, trans-9 and C16:1, trans-9. Trans fatty acids are produced as intermediates during rumen biohydrogenation.

The omega-3 fatty acids are found in trace amounts in bovine milk fat, constituting approximately 0.5 % of total fatty acids. Alpha-linolenic acid [C18:3, cis-9,12,15] is the predominant omega-3 fatty acid in bovine milk fat, and it acts as a substrate for the synthesis of very long chain omega-3 fatty acids [C20:5n-3, C22:5n-3, C22:6n-3]. Very long chain omega-3 fatty acids are functional food components and have been favorably related to human health. They are synthesized in the mammary gland of dairy cows from alpha-linolenic acid by the action of Δ-6 desaturase enzyme along with Δ-5 desaturase and elongase (Figure 3). Normally, the activity of Δ-6 desaturase enzyme in the mammary gland of dairy cows is limited [28], which might explain the low concentrations of omega-3 fatty acids in bovine milk fat. Linoleic acid [C18:2, cis- 9,12] is the predominant omega-6 fatty acid in bovine milk fat. Very long chain omega-6 fatty acids [C20:3n6, C20:4n6] are synthesized in the mammary gland by the enzymatic activity of Δ-6 and Δ-5 desaturases and elongases [29]. Overall, fatty acid synthesis in dairy cows seems to be a result of feed intake, intermediary metabolism, and body tissue mobilization.

Factors affecting milk fatty acid composition in dairy cows

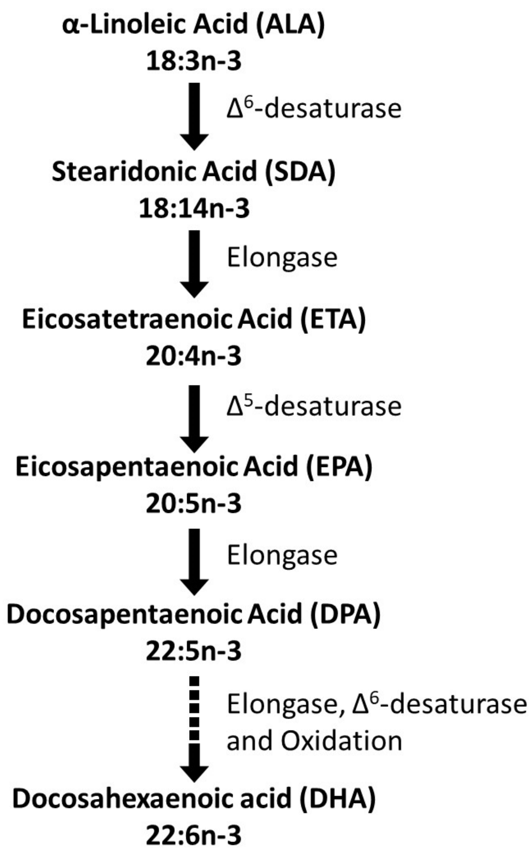

Figure 3. Biosynthesis of omega-3 fatty acids in dairy cows [29].

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Effect of production system

Diet plays a role in determining the fatty acid content of milk in dairy cows. The modification of the FA profile of bovine milk fat has been a long-term objective in a dairy enterprise. Milk from cows fed fresh forage, particularly fresh grasses and forage legumes, contains higher concentrations of more desirable unsaturated fatty acids than milk from cows fed silage or hay.

Forages are a cost-effective source of unsaturated fatty acids in ruminant diets. However, they contain lower levels of unsaturated fatty acids, which can be lost directly or indirectly during various processes of forage preservation, such as hay and silage making, as well as during rumen biohydrogenation [30]. Studies have suggested various nutritional manipulations to improve milk fat composition in a desirable direction. For instance, fatty acid supplementation decreases short and medium chain FA and C16:0 and increases C18:1 proportions of total FA in milk [31]. Additionally, replacing grass with red clover silage prepared at an early stage of maturity enhances the MUFA and PUFA content of milk [32]. Cow milk produced on red clover and white clover has higher contents of poly-unsaturated fatty acids, mainly C18:3n-3 [0.89%], than milk produced on grass [0.54%]; however, red clover slightly negatively affects milk fat and protein contents [33].

Effect of rumen microbes

The ruminal microbes will convert unsaturated fats to saturated fats in a sequence of events called biohydrogenation [34]. In principle, it appears that rumen biohydrogenation favors the synthesis of saturated fat, and the amount of unsaturated fatty acids could be increased by avoiding rumen biohydrogenation [29]. However, the process of biohydrogenation by bacteria is believed to be an attempt to protect themselves against the potential toxic effects of unsaturated fats on bacteria, particularly the fiber-digesting bacteria [35]. In case the feeding of unsaturated fats reduces the numbers or activity of fiber-digesting bacteria in the rumen, then feed intake, milk yield, and milk fat content are likely to go down. During the process of biohydrogenation of unsaturated fats in the rumen, the conversion to saturated fat could be incomplete and may result in the synthesis of several forms [isomers] of fatty acids, including some trans fatty acids [36] (Figure 2). Some of the trans fatty acids such as the trans-10, cis-12 conjugated linoleic acid [CLA], and the trans-10, C18:1 can have a remarkable impact on milk fat when they leave the rumen, are absorbed into the bloodstream, and are taken up by the mammary gland. These trans fatty acids can be formed by a diverse range of bacteria in the rumen during the biohydrogenation of unsaturated fatty acids [37].

Effect of physiological factors

As diet plays a major role in determining the fatty acid composition of bovine milk, it has received the most attention in the scientific literature. However, our knowledge of the effects of physiological factors such as parity, age at calving, and stage of lactation on the fatty acid composition of bovine milk is limited and mainly based on research conducted on limited data sets. There is conflicting evidence in the literature about the effect of parity on the fatty acid composition of bovine milk. Some studies noted that parity has a significant effect on the fatty acid composition of bovine milk [38]. In contrast, parity has been reported to significantly affect the contents of many fatty acids in the milk of US dairy cows [27], Nguni cows in South Africa [39], and Canadian Holsteins [27]. The effect of age at calving on the fatty acid composition of cow's milk is not clear [12].

Many studies have reported that the stage of lactation significantly affects the fatty acid composition of bovine milk [27,38,40,41]. Kgwatalala et al. (2009) observed that early lactation [<100 DIM] milk had significantly higher concentrations of oleic acid, trans vaccenic acid, C18:2, total monounsaturated fatty acids, and total polyunsaturated fatty acids as compared to either mid [100-200 DIM] or late [<200 DIM] lactation [38]. Stoop et al. (2009a) observed that the concentration of de novo synthesis fatty acids [C6:0 to C14:0] increased during the first three months of lactation and decreased afterward, whereas C18:0 followed an opposite pattern [42]. Other previous studies also reported similar findings, suggesting that the stage of lactation should be considered while studying bovine milk fatty acid composition [25,40,43].

Effect of genetics

Reliable estimates of genetic parameters for fatty acids proportions in milk fat are required to include such a breeding objective in dairy cattle selection indices. Heritability estimates for various individual fatty acids ranged from 0.09 to 0.54 [10], from 0.18 to 0.44 [44], from 0.09 to 0.28 [45], from 0.03 to 0.19 [46], from 0.04 to 0.28 [47], from 0.00 to 0.24 [9]. The details of different genetic studies on bovine milk fatty acids are reported in Table 1. [8]. In a study on 2573 Canadian Holstein cows reported genetic parameters of 33 fatty acids and suggested that selection for monounsaturated or selection against saturated fatty acids could improve milk fat profile in dairy cows [48]. In a nutshell, heritability estimates of some major individual saturated and monounsaturated fatty acids are as good as those of milk production traits, indicating that bovine milk fatty acid composition can be altered in a desirable direction using genetic selection tools.

Table 1. Details of studies involving estimation of genetic parameters for fatty acids in bovine milk.

Authors	Year	Breed	Country	Sample size	Herds	FA Analysis	Parity	DIM	Model
Bilal et al. [8]	2014	H	Canada	2573	46	GC	1-8	3-450	Animal
Bastin et al. [44]	2011	H	Belgium	26106	531	MIR	1	1-100	RRTD
Garnsworthy et al. [47]	2010	H	U. K.	2408	325	GC	1-3	56	Sire
Mele et al. [46]	2009	H	Italy	990	34	GC	1-7	7-450	Animal

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Stoop et al. [10]	2008	H	Netherland	1918	398	GC	1	63-263	Animal
Bobe et al. [9]	2008	H	U.S.A.	233	1	GC	1-10	1-10 months	Animal
Soyeurt et al. [45]	2007	H	Belgium	7700	25	MIR	1-3	5-365	RepTD

Note: H: Holstein; FA: fatty acid; DIM: Days in milk; GC: Gas chromatography; MIR: Mid-infrared spectroscopy; RRTD: Random regression test day model; RepTD: Repeatability test day model.

It is more appropriate to consider genetic correlations among individuals and groups of fatty acids and milk production traits before making any selection decision. Our knowledge of genetic associations between individual fatty acids is limited as few studies are available on this subject [8,10,45,46,49]. Overall, SFA were negatively genetically correlated with MUFA and PUFA, whereas genetic correlations between MUFA and PUFA were positive. The SFA showed positive associations with fat yield and fat percentage, whereas unsaturated FA were negatively associated with fat yield and fat percentage.

How to Improve the Fatty Acid Composition of Bovine Milk?

Negative consumer perception of milk fat is a concern of the dairy industry, and there is a growing interest in changing the milk fat composition of bovine milk in many countries. The ultimate goal of the dairy industry is to provide the best quality dairy products at the minimum possible cost. From the available literature, the direction of improvement in the fatty acid composition of milk seems pretty much clear. The proportions of saturated fatty acids are required to be decreased, and the proportions of unsaturated fatty acids are required to be increased in bovine milk fat. Two main factors which determine the fatty acid composition of milk are diet and genetics. The use of low-cost forages (especially fresh leafy grass and red clover silage) to change milk fat composition in a desirable direction is an attractive option; however, the effects of forages in changing milk fat composition are much smaller than feeding concentrate or ruminally protected fats [50]. The use of concentrate or inert fat in the diet of dairy cows may increase cost and would be effective as long as these compounds are being fed. A more long-lasting solution could be the genetic selection of dairy cows based on the fatty acid composition of milk, as reasonable additive genetic variation for milk fatty acids exists among dairy cows [8,10,46].

Currently, there is no selection program in place anywhere in the world that considers the relative proportions of the individual fatty acids in milk fat. However, the market demand for differentiated and healthy dairy products has increased in the recent past, and this may require large adaptations within the current production and breeding structure [10]. Currently, the dairy industry is moving from traditional quantitative genetic selection to genomic selection, which is expected to accelerate the rate of genetic gain, particularly the selection of young bulls [51]. Moreover, it is not beyond the scope of genomic studies to go for genetic selection for milk fat quality. Quantitative trait loci affecting milk composition of total saturated fatty acids, total unsaturated fatty acids, and the ratio of saturated fatty acids to unsaturated fatty acids, short, medium, and long chain fatty acids, have been localized using genome-wide- association studies [52-54]. These studies point to a promising prospect of the application of genome technology to genetically alter the fatty acids composition of bovine milk.

Future Prospects

Most of the few studies to date on genetic aspects of the fatty acid composition of milk used small data sets to estimate genetic parameters, mainly due to the cost and complexity involved in fatty acid determination using gas chromatography. A possible area of future research may include research for a cheaper but more accurate method of fatty acid determination from milk samples. It is suggested to explore the qualitative and health aspects of bovine milk fat in dairy animals, and efforts to improve the fatty acids composition of bovine milk along with increased milk production should be encouraged.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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