Pre- and postpartum effects of starch and fat in dairy cows: A review

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Abstract

This review discusses the effects of starch and fat before and after calving on metabolism, energy balance (EB), milk production, and reproduction in dairy cows. The shift in dairy cows from a pregnant non-lactating state to a non-pregnant lactating state induces physiological changes, which affect the metabolic and endocrine axes to redirect body energy stores towards the mammary gland for milk production. Overfeeding high starch and fat levels during the dry period after calving may result in cows failing to adapt to the negative energy balance (NEB) because of major liver and rumen dysfunction. Alternatively, keeping dry cows on high-forage/low-energy diets adjusts dry matter intake (DMI) to optimize the rumen function and decrease the severity of the NEB during transition. These periparturient biological improvements in dairy cows showed real benefits such as fewer postpartum health complications (e.g. milk fever, ketosis, mastitis, metritis), decreased body condition loss and improved reproductive axis in the subsequent lactation. Adding dietary starch and/or fat to diets of dairy cows following parturition increased milk yield. In addition, milk protein of dairy cows increased with glucogenic diets, but decreased with lipogenic diets. Inversely, milk fat usually increases after feeding lipogenic diets, but it decreases when feeding glucogenic diets to dairy cows. Glucogenic and lipogenic nutrients can affect the cow's metabolism and its EB status positively, as is evidenced by plasma non-esterified fatty acids (NEFA), β-hydroxybutyrate (BHB), glucose, amino acids, insulin, insulin-like growth factor-I (IGF-I), growth hormone (GH), gonadotropin hormones, and progesterone (P4) levels. These metabolites (NEFA, BHB, glucose, amino acids) and hormones (insulin, IGF-I, GH, P4) have been shown to affect folliculogenesis, ovulation, conception, and pregnancy success. Feeding a starch-based diet to dairy cows can lead to acidosis and increase glucose and insulin levels, while decreasing NEFA and BHB levels. Furthermore, an insulinogenic diet favours an early resumption of ovarian activity, but has adverse effects on the quality of oocytes. In contrast, keeping dairy cows on a fat-based diet elevates NEFA and BHB levels and decreases glucose and insulin levels. Additionally, a lipogenic diet increases the plasma P4 levels and improves the quality of oocytes. These evidences suggest that reproductive performances in dairy cows can be enhanced by feeding an insulinogenic diet until the resumption of the ovarian cycle then switching to a lipogenic diet from mating period onwards. Since long-term field studies on fertility are limited and the reproduction process in dairy cows is multi-factorial, further research is needed on the pre- and postpartum effects of starch and/or fat as well as their combinations on reproduction axis and thus to draw conclusions on reproductive performances.

Keywords: Digestion, energy nutrients, metabolism, milk production, reproduction, ruminant

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Introduction

Carbohydrate and fat-based feedstuffs are major energy components that are usually used in the diets of dairy cows (Schroeder et al., 2004; Carmo et al., 2015). Glucogenic-based feedstuffs provide the fermentable energy and improve the protein/energy balance to potentially enhance the supply of rumen microbial protein synthesis (MPS) to the small intestine (Rearte & Pieroni, 2001; Bargo et al., 2003).
Glucogenic-based ingredients consist of cereal grains and their milling by-products, molasses, beet and citrus pulps, roots and tubers such as cassava and potatoes and their by-products, and dried reclaimed bakery products (McDonald et al., 2002; Mosavi et al., 2012; Steyn et al., 2017). Fat increases the energy density of the diet (Schroeder et al., 2004), and in particular enhances plasma cholesterol, the major precursor for steriodogenesis, including luteal P4 synthesis in postpartum cows (Roche et al., 2011). Fat can be included in the form of ruminally inert sources such as hydrogenated fish fat, high melting point fatty acids, and calcium (Ca) salts of long-chain fatty acids or non-ruminally inert sources such as soybean oil and full fat rapeseed (Bargo et al., 2003). Manipulating the energy level and source in the diet of pre- and postpartum cows showed significant improvements in terms of decreased incidence of health problems (Beever, 2006), optimized rumen microbial activity (Jouany, 2006), increased amount of digested nutrients from the gastro-intestinal tract (GIT) (Bauman & Currie, 1980), decreased body condition loss (Drehmann, 2000; Butler, 2003), and increased milk responses (Grum et al., 1996; Ingvartsen & Andersen, 2000; Cavestany et al., 2009a; Reis et al., 2012; Damgaard et al., 2013; Roche et al., 2013; Hills et al., 2015). However, studies on the pre- and postpartum effects of starch- or fat-based diets on dairy cow reproduction parameters are contradictory, with some studies reporting a negative effect or lack of effect of it (Beam & Butler, 1997; Oldick et al., 1997; Oldick et al., 1998; McNamara et al., 2003; Van Knegsel et al., 2007c; Dyck et al., 2011; Gilmore et al., 2011), compared with other studies that reported a positive effect (Gong et al., 2002; Cavestany et al., 2009b; Garnsworthy et al., 2009; Reis et al., 2012; Little et al., 2016; Thatcher, 2017). The objectives of this review are therefore to discuss the effects of energy-based diets containing starch and/or fat during the dry and postpartum periods on the subsequent metabolism, milk production and fertility of dairy cows.

**Energy sources during the dry period**

A lactation period of 305 days, followed by a dry period of 56 to 60 days, has been regarded as a strategic management system for most dairy farms since the 1950s (Bachman & Schairer, 2003). The dry period is defined as a period of preparation, allowing body and conceptus growth in heifers and body restoration and conceptus growth in dry cows, in anticipation of the next lactation (NRC, 2001; Beever, 2006). Through homeorhetic controls, the imposition of pregnancy during this period favours the partition of specific nutrients (i.e. glucose and amino acids) not only for foetal growth (i.e. about 60% relative to the calf live weight at birth), but also for the growth of the foetal membranes, the gravid uterus, and the mammary gland (Bauman & Currie, 1980). However, the feed intake of heifers and dry cows usually declines in the late dry period relative to their energy requirements (Grummer, 1995; Huzzey et al., 2007), triggering the beginning of the NEB (Butler, 2003). The decrease in prepartum DMI can be attributed to digestive, hormonal, physiological and immunological factors related to this period, and to the rapid growth of the foetus, which takes up the abdominal space, thereby decreasing the rumen volume (Jouany, 2006; Wankhade et al., 2017). Everitt (1964) reported that the foetus of a ruminant is more vulnerable than that of many other species to maternal undernutrition stresses, which impede normal foetal growth. Thus, maternal adaptations during late pregnancy partitioned the nutrients in heifers and dry cows that are required for their own maternal growth and replenishment of protein and energy reserves to meet the foetal requirements (Bauman & Currie, 1980).

Several studies have investigated and reviewed the possible benefits of starch- and fat-based ingredients in prepartum diets of dairy cows (Grum et al., 1996; Drackley, 1999; Agenäs et al., 2003; McNamara et al., 2003; Dann et al., 2005; Janovick & Drackley, 2010; Janovick et al., 2011; Damgaard et al., 2013). However, results are limited, and in some instances are conflicting, with certain studies showing a positive prepartum effect on EB status (Grum et al., 1996; Janovick & Drackley, 2010; Janovick et al., 2011; Damgaard et al., 2013), milk yield (Ingvartsen & Andersen, 2000; Cavestany et al., 2009a), milk composition (Cavestany et al., 2009b; Grum et al., 1996; Damgaard et al., 2013), and reproduction performance (Cavestany et al., 2009b), with others reporting the lack of effect on these traits (McNamara et al., 2003; Agenäs et al., 2003; Burke et al., 2010; Mann et al., 2015). Unrestricted feeding of a diet containing higher energy levels (starch or fat) to prepartum cows enhanced DMI, allowing them to consume too much energy relative to their nutritional requirements, compared with those being fed a lower energy density diet (Janovick & Drackley, 2010). Overconsuming starch increased the osmolality of the rumen contents and inflamed the rumen epithelium, resulting further in hepatic fat deposition (Beever, 2006) and a greater decline in DMI (Minor et al., 1998; Olsson et al., 1998). Furthermore, feeding prepartum high starch diets increased the production of volatile fatty acids (VFAs) and resulted in a decrease in pH below 5.5 and an accumulation of lactic acid in the rumen. This decline in DMI and ruminal pH exacerbates the EB deficit in cows (Jouany, 2006). Alternatively, the overconsumption of fats results in inhibitory effects on microbial fermentation and sensitivity to nutrient imbalances in the rumen, causing reduced DMI (Palmquist, 1994). Additionally, feeding high prepartum levels of dietary fat negatively affected the EB status, as is evidenced by increased plasma...
NEFA and BHB levels and decreased insulin levels (Leroy et al., 2008b; Damgaard et al., 2013), which result in longer anoestrous periods in the subsequent lactation (Giuliodori et al., 2011). In both energy feeding contexts, dry cows can possibly fail to adapt to the NEB stress when fed high prepartum levels of starch and fat due to the associated metabolic and rumen dysfunctions (Jouany, 2006; Janovick et al., 2011; Mann et al., 2015). Furthermore, a severe NEB during the prepartum period has been associated in the subsequent lactation with increased health problems (e.g. retained placenta, ketosis, abomasum displacement, lameness, mastitis, and endometritis) (Duffield et al., 2009; OSPina et al., 2010a; McArt et al., 2012), reduced reproductive success, and decreased milk production (Duffield et al., 2009; OSPina et al., 2010b; 2010c).

The optimal prepartum dietary management strategy with reference to the types and levels of energy intake and control of DMI is still to be developed (Janovick & Drackley, 2010). Some studies indicated that an overconsumption of energy prepartum is detrimental to postpartum cow health and liver function (Grum et al., 1996; Rukkwamsuk et al., 1999), whereas others demonstrated that supplementing extra energy during the dry period is beneficial to transition success (Dann et al., 1999; Rabelo et al., 2005). Consequently, recent studies investigated the potential benefits of feeding fibre-based diets containing > 400g/kg of NDF and low digestible energy levels on DM basis during the dry period (Janovick et al., 2011; et al., 2013; Mann et al., 2015). Such prepartum diets were reported to adjust the DMI, which optimized the rumen digestion and fermentation (Jouany, 2006) and decreased the mobilization of body reserves, as well as the deposition of lipid and tri-acyl glycerol (TAG) in the liver (Mann et al., 2015). Controlling the energy content in prepartum diets is usually achieved by adding bulky lower-quality forages such as chopped wheat straw or oat hay, which increase fibre content and limit the voluntary DMI (NRC, 2001), thereby regulating total nutrient consumption. Maintaining pregnant dry cows on high-forage/low-energy diets has shown significant improvements in their subsequent lactations in terms of fewer health problems (e.g. ketosis, abomasum displacement, and fatty liver syndrome), reduced body condition loss, and improved reproductive axis (Drehmann, 2000; Beever, 2006; Jouany, 2006). Thus, the evidence revealed that feeding a prepartum forage-based diet containing low digestible energy level optimized the GIT and rumen microbial activity (Jouany, 2006), improved metabolic status, and reduced the risks of ketosis and fatty liver syndrome in periparturient dairy cows (Janovick et al., 2011; Vickers et al., 2013; Mann et al., 2015). However, long-term feeding trials that investigated the prepartum effect of energy levels and sources and their combinations on the postpartum milk responses and reproductive performances of dairy cows are limited, making it difficult to draw final conclusions.

Negative energy balance and postpartum-related disorders in dairy cows

Over the past few decades, a significant increase in milk yield has been observed in dairy herds (Leroy et al., 2008b; 2008c; Roche et al., 2011) as a result of intense genetic selection, improved nutrition, and better cow management (Lucy, 2001; Thatcher et al., 2011). However, several studies have shown that the improvement in milk yield is associated with some negative consequences, such as increased occurrence of metabolic and infectious diseases and a decline in reproductive performance (Lucy, 2001; 2007; Butler, 2003; Walsh et al., 2011; Watthes, 2012; Thatcher et al., 2017). As indicators of reproduction management efficiency, the calving interval and the number of artificial inseminations (Al) per conception have increased substantially worldwide (Butler, 1998). In South African Holsteins for instance the intercalving period increased from 386 days in 1986 to 412 days in 2004 (Makgahlela, 2008).

During the transition period from a pregnant non-lactating state to a non-pregnant lactating state, dairy cows are confronted with numerous physiological challenges and stressors related to parturition and the onset of lactation (Evans & Walsh, 2012; McArt et al., 2013; Esposito et al., 2014). One of the main challenges is a rapid rise in nutrient requirements (Ingvartsen, 2006), essentially doubling overnight once milk production begins (Drackley et al., 2005). In the week preceding calving, the cow’s appetite decreases (Walsh et al., 2011) and the DMI has been reported to decline by approximately 30%, occurring within 24 hours before calving (Huzzey et al., 2007). Thus, cows enter into a NEB status and mobilize stored triglycerides from adipose tissues in an attempt to meet the energy requirements (Rukkwamsuk et al., 1999). The NEB starts a few days before calving until 70 to 84 days post partum, coinciding with the beginning the breeding season (Butler, 2003; Roche et al., 2009). The NEB impairs the general metabolic system in dairy cows and has been identified by a number of researchers (Butler & Smith, 1989; Garnsworthy & Webb, 1999; Butler, 2003; Jorritsma et al., 2003) as an underlying causal factor of poor lifetime milk production and reproductive performance

Several reviews have been published regarding the effect of the EB status on reproductive efficiency of dairy cattle (Beam & Butler, 1999; Butler, 2000; 2003; Jorritsma et al., 2003; Van Knegsel et al., 2005; Watthes et al., 2007; Santos et al., 2008; Roche et al., 2011; Evans & Walsh, 2012; Leroy et al., 2014). The status of NEB alters the insulin level and the GH-IGF-I axis to decrease the bioavailability of circulating IGF-I (Watthes et al., 2007). Furthermore, it decreases the luteinizing hormone (LH) pulse frequency, the diameter
and growth rate of the dominant follicle, the activity of the corpus luteum, and perioestrous hormone levels such as oestradiol and P₄ (Beam & Butler, 1997; 1999; Butler, 2000). The effects of these EB-induced alterations on fertility have resulted in increased number of days from calving to the resumption of oestrus and days open and to decreased conception rates following fertilization and pregnancy survivals afterwards (Giuliodori et al., 2011; Roche et al., 2011).

When dairy cows experience a NEB, their immune system is likely to be compromised (Mallard et al., 1998; Wankhade et al., 2017). The level of impairment and the degree of reclamation of postpartum immune competence are influenced strongly by the extent and duration of the NEB around calving (Pyörälä, 2008; Watthes et al., 2009), making cows in a severe NEB more vulnerable to infections caused by pathogenic organisms (Goff, 2006; Watthes, 2012). Gröhn et al. (1995) studied the prevalence of postpartum diseases in multiparous cows in 25 Holstein herds in North America and found 7.4% incidence of retained placenta, 7.6% incidence of metritis and 4.9% incidence of ketosis. Jordan & Fourdraine (1993) surveyed 61 top milk-producing herds in North America and reported 3.7% incidence of ketosis, 9.0% incidence of retained placenta and 12.8% incidence of metritis. Other reports found that the effects of metabolic biomarkers (i.e. high NEFA and BHB) due to poor adaptation of lactating cows to the energy stress were associated with the occurrence of abomasum displacement, clinical ketosis, lameness, mastitis, and endometritis, which all can contribute to an increased risk of culling of affected animals (Selfi et al., 2011; Walsh et al., 2011; Evans & Walsh, 2012; Esposito et al., 2014). Metabolic and infectious diseases can lead to lower milk yields (Rajala-Schultz et al., 1999a; 1999b), lower conception rates (LeBlanc et al., 2002; Hansen et al., 2004; Bisinotto et al., 2012), and increased incidences of involuntary culling (Gröhn et al., 1998; Esposito et al., 2014).

Energy partitioning in dairy cows

Feed constituents such as dietary fibre, starch and protein provide substrates for rumen microbial fermentation, which yields gases (with the main ones being methane or CH₄, carbon dioxide or CO₂ and hydrogen or H₂), MPS, and VFA. Rumen VFAs provide energy in dairy cows and the main ones are acetate, butyrate, and propionate. Fat is hydrolysed into fatty acids and hydrogenated in the rumen. Ruminal bypass nutrients and microbial matter can be digested and absorbed in the small intestine, providing additional glucogenic and lipogenic as well as amino acids compounds to the animal (McDonald et al., 2002). These absorbed nutrients proceed in the liver through a succession of pathway reactions of the Krebs cycle involving oxygen (respiratory chain reactions) to produce the body energy fuel as adenosine triphosphate (Van Knegsel et al., 2005).

As parturition occurs and dairy cows shift into producing milk, the requirement for nutrients increases because of the onset of lactation and also of the initial depression of DMI around parturition (Walsh et al., 2011; Evans & Walsh, 2012). Requirements for glucose and metabolizable energy (ME) increase by two- to threefold after the onset of the lactation (Drackley et al., 2001). Also, an increase occurs in postpartum plasma GH levels, thus prioritizing high milk synthesis in the mammary gland (Chagas et al., 2007). In the liver, the improvement in plasma GH levels directly stimulates gluconeogenesis and indirectly antagonises the production of insulin, necessary for meeting the glucose demands for milk production (Lucy, 2004). As a result of low plasma glucose and insulin levels, body fat and, to a lesser degree, body protein stored as body reserves are mobilized (Van Knegsel et al., 2005), usually through homeostatic regulation (Roche et al., 2009; Thatcher et al., 2011). This mobilization results in a loss of body condition score and live weight (Jorritsma et al., 2003; Van Straten et al., 2008) as a physiological mechanism to overcome the energy deficit. Non-esterified fatty acids are consequently released from body fat reserves, with increasing NEFA levels in the bloodstream, suggesting an EB shortfall (Duffield, 2000; Watthes et al., 2007). The NEFA metabolites are directed into the mammary gland to supply milk triglycerides (Drackley, 2000) or utilized in the liver (Drackley et al., 2001; Vernon, 2002; Schulz et al., 2014). Following their uptake by the liver, NEFA can be utilized in three pathways. First, NEFA can be oxidized to carbon dioxide to supply energy as alternative energy fuel for other tissues, while most of the glucose is diverted for lactose synthesis in the mammary gland (Vernon, 2002). Second, it can be partially oxidized to produce ketone bodies, acetone, aceto-acetate and BHB, which may result in ketosis (Schulz et al., 2014; Esposito et al., 2014). Third, it may be esterified to triglycerides or phospholipids and stored in the liver as TAG, with the possibility of causing fatty liver syndrome (Drackley et al., 2001). This mobilization highlights that the metabolic effects of a NEB status in early lactation induce an imbalance in the ratio of plasma glucogenic and lipogenic compounds derived from feed nutrients and body reserves (Schulz et al., 2014). Hence, the physiological consequences of postpartum EB deficit causes low plasma glucose and insulin levels associated with high levels of plasma NEFA, BHB, acetone, acetoacetate, and liver TAG (Van Knegsel et al., 2005; Evans & Walsh, 2012). As lactating cows enter a state of NEB, physiologically they direct the limited available nutrients in their system to milk synthesis for the survival of living offspring. This prioritization occurs at the expense of the reproductive axis, thus limiting the dominant follicle to ovulate, be fertilized and cared for during an entire
gestation (Leroy et al., 2008a). From this brief review, it appears that the brain, GIT, body reverses, foetus (before calving), and the udder, as well as the reproductive organ (after calving), are all components in the adaptation to EB status in dairy cows. In addition, the liver obviously plays a key role in coordinating metabolic responses in dairy cows in order to adapt and recover from NEB.

Several studies have indicated that dietary energy sources can be manipulated through inclusion of feedstuffs in the diet to prevent and/or treat NEB-related disorders (Staples et al., 1998; Gong et al., 2002; Jorritsma et al., 2003; Van Knegsel et al., 2005; 2007a; 2007b; 2007c; Gilmore et al., 2011; Thatcher et al., 2011). McGuire et al. (2004) reported that the improvement in DMI is the critical factor in dairy cows in meeting the energy needs for greater amounts of milk produced in early lactation without a more prolonged period of NEB. In addition, increasing levels of glucogenic or lipogenic dietary components in a diet of dairy cows change plasma energy biomarkers to reduce adverse metabolic and infectious disorders and improve milk synthesis and reproductive function. Lipogenic ingredients that stimulate the production of butyrate and acetate in the rumen are expected to increase the ratio of plasma lipogenic/glucogenic compounds (Van Knegsel et al., 2005). In addition, feeding dietary fat results in increased energy partition into milk and consequently limits the energy partition into body reserves (Van Knegsel et al., 2007a). In contrast, glucogenic nutrients (grains, cassava and potatoes and their by-products) are either fermented in the rumen to stimulate the production of propionate or bypass the rumen and are absorbed in the small intestine as glucose. Consequently, glucogenic nutrients can increase insulin and glucose levels, thus decreasing the ratio of plasma lipogenic/glucogenic compounds (Van Knegsel et al., 2005). As a result of improved insulin and glucose levels, dietary starch stimulates body fat deposition and energy partitioning into body tissue (Van Knegsel et al., 2007a). When dairy cows are fed a starch- or fat-based diet in excess of their daily nutritional requirements, as milk production begins to decline in the final third of the lactating period, they regain a positive EB. At this time, the EB recovery, as evidenced by an increase in plasma insulin and glucose levels, allows the stimulation of the enzyme acetyl-CoA carboxylase in the liver (Drackley, 2000). This hepatic enzymatic activation promotes the restoration of body fat through lipogenesis (Bauman & Currie, 1980) in anticipation of the next lactation (Friggens, 2003).

**Effect of energy sources on metabolism of dairy cows**

Cereal grains, such as maize, are fed primarily to provide energy to dairy cows and most of the digestible energy in cereal grains comes from starch (Ali et al., 2012). Levels of starch can range up to 30% on a DM basis of the diet in lactating dairy cows (Akins et al., 2014). Most of the starch is hydrolysed by various routes to pyruvic acid, which is then fermented in the rumen. The ruminal fermentation process increases the production of VFAs and greenhouse gases (CH₄, CO₂ and H₂). The VFAs and greenhouse gases are absorbed through the rumen wall and lost by eructation, respectively. Starch also affects the protein/energy balance and the rumen MPS in ruminants (Rearte & Pieroni, 2001; Bargo et al., 2003). The rest of the starch, bypassing rumen fermentation, is digested by pancreatic enzymes and absorbed in the small intestine as glucose (Norberg et al., 2007). In dairy cows, the addition of starch to the diet decreases the energy loss through energy sparing from gluconeogenesis and results in a decrease in CH₄ production per unit of product through the increase in the efficiency of animal production (McDonald et al., 2002). Furthermore, dietary starch is efficient in alleviating the NEB, suggesting a reduced postpartum risk of metabolic disorders (Van Knegsel et al., 2007c). However, feeding high levels of starch can increase the risk of ruminal acidosis, diminish ruminal fibre digestibility, reduce the ruminal acetate/propionate ratio, and decrease the synthesis of milk fat in the udder (Bargo et al., 2003).

Dietary fat improves the energy density of the diet and increases the synthesis of milk fat in the mammary glands of dairy cows (Schroeder et al., 2004). It is almost entirely hydrolysed into fatty acids and hydrogenated in the rumen and subsequently absorbed from the small intestine (Doreau & Ferlay, 1994). Adding more than 8–9% of fat to the diet may result in milk fat and milk protein depression in the udder owing to its negative effect on DMI and rumen fermentation of fibre in particular (Schroeder et al., 2004). To overcome these complications and to improve the energy intake, interest has increased in feeding ruminally inert fats, such as Ca-salts of long-chain fatty acids, to lactating dairy cows (Schneider et al., 1988). The Ca-salts of long-chain fatty acids are energetically dense and consist of about 51.6% palmitic acid, 5.9% stearic acid, 35.4% oleic acid, and 6.2% linoleic acid (Schneider et al., 1988). In the rumen, these fats are insoluble and inert at ruminal pH variations (Chalupa et al., 1986) and decrease CH₄ production per DMI without any decrease in digestibility (Holter & Young, 1992). In the abomasum, the fats are broken down by hydrochloric acid to free fatty acids and Ca-ions. The rumen bypass of these fats consequently increases their absorption from the small intestine, potentially enhancing the supply of polyunsaturated fatty acids to the mammary gland (Purushothaman et al., 2008). Such synthesis of milk with modified fat composition has been associated with decreased risk of chronic diseases, including heart disease in humans (Lock & Bauman, 2004).
The inclusions of dietary starch and fat into diets of dairy cows have been demonstrated to be effective in reducing the extent and duration of NEB during early lactation (Williams & Stanko, 2000; Van Knegsely et al., 2007c; Garnsworthy et al., 2009). As nutrients are digested and absorbed through the GIT, a number of metabolic and hormonal signals released from the liver, pancreas, muscle and adipose tissues act on brain centres, regulating the DMI, EB and metabolism of dairy cows (Chagas et al., 2007). The signals, which can include glucose, fatty acids, insulin, IGF-I, glucagon, GH, ghrelin, leptin, and perhaps myostatin, trigger their receptors by means of positive and negative endocellular feedback mechanisms to regulate DMI, body growth and reserves, milk synthesis, and the reproductive axis (Chagas et al., 2007; Lucy, 2007; Garnsworthy et al., 2008a; Roche et al., 2009; Wathes, 2012; Esposito et al., 2014; Wankhade et al., 2017). At the ovarian level, the reproductive axis is regulated by the hormones of the hypothalamus (gonadotropin-releasing hormone (GnRH)), anterior pituitary (follicle-stimulating hormone (FSH) and LH), ovari (P₄, oestradiol and inhibins), and the uterus (prostaglandin-F₂α (PGF₂α)) through a system of positive and negative feedback signals governing the oestrous cycle in dairy cows (Forde et al., 2011). The ovarian follicular growth and development are characterized by consecutive follicular waves, that is, in three dairy cows and two in heifers per oestrous cycle. Each wave begins with the recruitment of a cohort of follicles from the established fixed number of primordial follicles during foetal development and finishes with the selection of a dominant follicle (Webb et al., 2004). While other recruited follicles undergo atresia, the dominant follicle continues to grow and mature in the preovulatory stage and eventually ovulates. When cows are in a NEB condition, NEFA and BHB are released from body reserves and used as an alternative energy fuel for other tissues (Vernon, 2002; Esposito et al., 2014; Schulz et al., 2014). Second, the somatotropic axis (consisting of GH, GH receptor and IGF-I) becomes uncoupled in the liver (Thatcher et al., 2010). Third, less ghrelin is released from the abomasum and more GH from the anterior pituitary gland (Chagas et al., 2007). Furthermore, less insulin, IGF-I and leptin are released from the pancreas, liver and adipose tissue, respectively (Leroy et al., 2008b). Lastly, these altered endocellular signals further attenuate the LH pulse frequency and decrease the production of GnRH (Butler, 2003) and therefore suppress altogether the reproductive axis (Chagas et al., 2007). Such metabolic and hormonal depressions, as dictated by the degree and duration of the NEB, influence the ovarian function negatively in terms of the number of follicles, the rate of follicular growth and development, the size of the ovulatory follicle and the quality and viability of the oocyte (Lucy et al., 1991; Boland et al., 2001; Butler, 2003; Diskin et al., 2003; Lucy, 2003; Webb et al., 2004; Garnsworthy et al., 2008a). In contrast, improvements in these feedback-regulated metabolites (e.g. glucose, amino acids, fatty acids) and hormones (e.g. insulin, IGF-I and leptin) regulate the hypothalamic-pituitary-ovarian-uterine axis positively to enhance fertility outcomes of dairy cows (Leroy et al., 2008a; 2008b; 2008c).

Feeding diets that are designed to increase insulin levels during early lactation may increase the proportion of cows ovulating before 50 days post partum (Gong et al., 2002; Van Knegsely et al., 2005). Adding dietary starch to the diets of dairy cows can improve insulin and glucose levels (Lammoglia et al., 1997) and reduce NEFA and BHB levels during the NEB period (Van Knegsely et al., 2007b) to eventually promote the resumption of the oestrous cycle (Garnsworthy et al., 2008b). However, high starch diets may suppress the appetite and thus DMI by inducing satiety and shorter meals (Thatcher et al., 2011). Furthermore, excessive insulin and IGF-I levels from high starch diets may overstimulate the ovary to negatively affect the developmental competence of oocytes (Leroy et al., 2008c). This overstimulation results in the production of inferior oocytes owing to uncoupled transcriptional factors (i.e. maternal messenger RNA and protein molecules) in the dominant follicle to acquire the full competence before ovulation (Armstrong et al., 2001). Poor transcription of these factors significantly reduces the quality and viability of the oocyte and after fertilization decreases the survival of the embryo prior to embryonic genome activation, which occurs at the 8–16 cell stage (Leroy et al., 2008b; 2008c). In contrast, the inclusion of dietary fat in a diet of dairy cows enhances the diet energy density stimulating milk synthesis, and yields higher NEFA and BHB levels associated with lower glucose and insulin levels (McNamara et al., 2003; Van Knegsely et al., 2005, 2007b; Moallem et al., 2007). Furthermore, feeding dietary fat increases the number and size of follicles, and the oestradiol production of the preovulatory follicle (Lucy et al., 1991; Beam & Butler, 1997; Moallem et al., 2007), most likely via the induction of high cholesterol and IGF-I levels in follicular fluid and plasma (Van Knegsely et al., 2007a; Esposito et al., 2012). Vasconcelos et al. (2001) reported that an increased follicle size can have advantageous effects on both oocyte quality and corpus luteum function. The resulting high plasma cholesterol concentration improves PGF₂α and P₄ secretion (Staples et al., 1998; Staples & Thatcher, 2005; Leroy et al., 2014), thus supporting embryo development and pregnancy survival (Ryan et al., 1992; Lammoglia et al., 1996; McNamara et al., 2003).

Obviously, manipulating the levels and types of energy feedstuffs containing dietary starch and fat can be a key tool in decreasing energy metabolic loss and optimizing the EB status of dairy cattle, while enhancing metabolic efficiency. This indicates that feeding starch- and fat-based diets to dairy cows can increase productivity and thus reduce CH₄ emissions per unit of production. However, a number of hormonal
and metabolic signals are involved for successful reproduction of heifers and lactating cows, making physiological pathways with many inter-related factors complex (Chagas et al., 2007; Garnsworthy et al., 2008a).

Effect of energy sources on milk yield and milk composition

Increasing fat- and starch-based ingredients in the daily diet raised the milk production of dairy cows (Van Knegsel et al., 2005; Reis et al., 2012; Higgs et al., 2013; Roche et al., 2013). A possible explanation for the improved milk production can be attributed to the amount of energy intake, increasing the ME intake with both starch and fat ingredients (Bargo et al., 2003; Hills et al., 2015). Such an enhancement in ME intake was reported to affect lactation persistence positively (Hermansen, 1990; Reis et al., 2012). Supporting this response, previous studies reported enhanced milk production as a result of increased energy intake (Erickson et al., 1992; Chouinard et al., 1997; Moallem et al., 2000). However, other studies reported no effect on milk yield when feeding enriched starch- or fat-based diets or combinations (Garnsworthy et al., 2008b; 2008c; 2009; Gilmore et al., 2011; Little et al., 2016). These researchers suggested that the lack of a significant effect on milk production could be attributed to the use of isocaloric diets in the studies.

Milk lactose percentage of dairy cows increased with the inclusion of dietary starch, but decreased with the addition of dietary fat (Van Knegsel et al., 2007c). However, other studies reported no effect on milk lactose percentage when starch or fat was added to diets of dairy cows (Van Knegsel et al., 2007a; Garnsworthy et al., 2008b; 2008c; 2009). The reason for these differences may be related to a limited capacity of the mammary gland to absorb increased glucose from the blood or to low plasma glucose available for lactose synthesis during early lactation (Piccioli-Cappelli et al., 2014). Milk protein percentage of dairy cows decreased with lipogenic diets (Erickson et al., 1992; Harrison et al., 1995; Chouinard et al., 1997). This inverse effect may be explained by the limitation in rumen microbial synthesis and gluconeogenesis with fats, leading to poor protein synthesis in the udder (Palmquist, 1988). However, glucogenic diets increased the milk protein percentage of dairy cows (Voigt et al., 2003), which may be attributed to greater plasma insulin levels (McGuire et al., 1995; Van Knegsel et al., 2007b), an enhanced MPS in the rumen (Carmo et al., 2015) and a greater mammary protein synthesis (Hills et al., 2015).

Milk fat percentage was usually enhanced after feeding lipogenic diets, but decreased when feeding glucogenic diets to dairy cows (Van Knegsel et al., 2007a; 2007b; Garnsworthy et al., 2008b; 2008c; Reis et al., 2012). However, overfeeding dietary starch or fat to lactating cows could lead to a depression in milk fat yield. Van Knegsel et al. (2007b) reported that an increase in insulin levels, induced by increased propionate from rumen digestion of starch, can promote glucogenesis over lipogenesis owing to low availability of fat precursors, to subsequently reduce the fat synthesis in the udder and milk energy output. Another report argued that the depression in milk fat content is possibly caused by an accumulation of trans fatty acids in the rumen because of the low pH with high starch diets (Kalscheur et al., 1997). Bauman & Griinari (2001) found that the decrease in milk fat content when overfeeding fat is generally attributed to altered rumen function, fat biohydrogenation and ruminal formation of trans-10 C18:1 fatty acids. Gama et al. (2008) pointed out that an increased supply of trans-10 cis-12 conjugated linoleic acid over other fatty acids to the udder was responsible for milk fat depression in dairy cows. This fatty acid has been recognized as a possible inhibitor of milk fat synthesis, decreasing the activity of lipogenic enzymes in the mammary gland (Baumgard et al., 2002).

Effect of energy sources on reproductive efficiency of dairy cows

Successful reproduction in dairy heifers and cows is the consequence of a chain of events, which consists of the establishment of oestrus in heifers and resumption of postpartum oestrous function in cows, the development and ovulation of a viable oocyte, conception, embryo development, implantation in the uterus, maintenance of pregnancy, and eventually calving (Garnsworthy et al., 2008a). A disturbance at any of these steps results in the failure of a successful conception and embryonic/pregnancy survival (Leroy et al., 2008a; 2008b). Because of this, the fertility of dairy cows is defined as a multi-factorial trait (Butler, 2003). The general decline in fertility has been attributed to a network of genetic, environmental, and managerial factors and their interactions, making it difficult to determine the exact reason for the deterioration in cow fertility (Walsh et al., 2011). So, for example, a decline in the fertility of dairy cows has transpired to reduced ability of the uterus to recover after calving, longer anovulatory periods and behavioural anoestrous, poor oestrus signs, irregular oestrous cyclicity, poor oocyte quality, poor fertilization, abnormal embryonic implantation and foetal development, uterine/placental incompetence, and pregnancy loss (Mwaanga & Jaworski, 2000; Lucy, 2007; Wathes et al., 2007; Leroy et al., 2008c; Evans & Walsh, 2012).

Endocrine status, the interval from calving to first oestrus, conception rate, and pregnancy maintenance are all altered when reduced DMI and longer periods of NEB are manifested in cows (Mwaanga
Increasing the amount of dietary starch and fat in the diet reduced the interval from calving to first ovulation and therefore initiated earlier postpartum cyclicity in cattle (Lammoglia et al., 1996; Gong et al., 2002; Santos et al., 2008; Burke et al., 2010). The early resumption of oestrous activity can be attributed to the improved EB status as the somatotropic axis synergises with the gonadotropins on ovarian cells, allowing the dominant follicle to ovulate and resuming the oestrous cycles afterwards. However, other studies reported no or negative effects of the energy intake level on the number of days from calving until the first oestrus (Beam & Butler, 1997; 1998; Garcia-Bojall et al., 1998; Oldick et al., 1997; Garnsworthy et al., 2009). Gong et al. (2002) reported increased conception rates following the first insemination when feeding dietary starch. In contrast, other investigations found no or negative effects of the energy intake level on the conception rate following the first insemination (McNamara et al., 2003; Garnsworthy et al., 2009; Gilmore et al., 2011). Furthermore, some studies found improved pregnancy rates when feeding dietary starch or fat to dairy cows (Burke et al., 2010; Reis et al., 2012), while others reported no or negative effects (McNamara et al., 2003; Dyck et al., 2011; Gilmore et al., 2011). However, important enhancements in conception rates were observed when feeding a diet that increased glucose and insulin levels in the early postpartum period and then switching to a diet that reduced insulin levels during the mating period, compared with other treatments (Garnsworthy et al., 2009). Furthermore, pregnancy rates for first and second services were enhanced when grass silage was supplemented with a similar concentrate fed to cows individually, based on the milk yield of the previous week, compared with those on a mixed diet containing grass silage and concentrate in a 50/50 ratio on a DM basis (Little et al., 2016). In contrast, Gilmore et al. (2011) found no improvements in pregnancy rates when feeding a glucogenic diet in early lactation to encourage the resumption of oestrus followed by a lipogenic diet to promote embryonic development, compared with other treatments. These researchers suggested that the lack of significance was due to the small number of animals used in the study.

Several causes could contribute to the inconsistency in effects of dietary starch and fat on the reproduction performance of dairy cattle in previous studies. First, the levels and types of dietary fat (chain length and degree of saturation of long-chain fatty acids) and starch (rate of fermentation in the rumen and proportion of rumen bypass starch) directly affected the profile of nutrients absorbed through the GIT and indirectly acted on the EB status, both of which probably influenced the ability to conceive and remain pregnant (Staples et al., 1998; Van Knegsel et al., 2007a; Leroy et al., 2008c; Roche et al., 2011). Second, it is critical to distinguish between non-isocaloric and isocaloric diets in studies, since the energy density, defined by the nutrient content (starch versus fat), has been described as having significant effects on reproductive efficiency (Van Knegsel et al., 2005). Another source of variation could be differences in numbers of animals, protocols and interpretations of experimental results among studies (McNamara et al., 2003; Gilmore et al., 2011).

Usually, feeding dietary starch that promotes glucose and insulin levels (Garnsworthy et al., 2008b) favours an early resumption of the first postpartum ovulation (Gong et al., 2002), while decreasing the quality of oocytes (Armstrong et al., 2001) and the conception rate (Leroy et al., 2008b). Plasma NEFA and BHB levels are increased and insulin levels are decreased with dietary fat inclusion (Leroy et al., 2008c), resulting in a longer anoestrous period (Giuliodori et al., 2011). However, dietary fat improves the quality of oocytes and corpus luteum (Beam & Butler, 1997; Vasconcelos et al., 2001), while increasing the P4 levels to enhance the pregnancy success (Roche et al., 2011). These results support the possible existence of nutritional signals associated with dietary energy levels and sources, dependently or independently of EB, which influence the reproduction axis through signals to the hypothalamus, pituitary, ovarian, oviductal, and uterine organs (Wathes et al., 2007). These observations suggest that the nutrient requirements for early resumption of ovarian cycles, follicle development and embryo development may be quite different in dairy cows, reflecting a potential advantage in diet alteration to ensure successful reproduction. This modification consists of feeding a glucogenic diet in early lactation to improve insulin levels for the resumption of oestrous activity, followed by a lipogenic diet before the breeding period to enhance cholesterol levels for oocyte quality and conceptus development. This feeding strategy has shown improved reproductive performance by feeding insulinogenic and lipogenic diets at different stages of the reproductive cycle (Garnsworthy et al., 2009). Despite all the progress made in this field, the physiological pathways explaining the link between EB indicators, hormonal and metabolic signals and their receptors, and pregnancy success remain, to a certain extent, unclear (Chagas et al., 2007). Additionally, feeding trials that investigated the interactions of energy levels and sources and their combinations from calving to mid or late lactation on reproductive performances are limited, thus making it difficult to draw final conclusions.

**Conclusion**

Inclusion levels and types of dietary energy sources, such as starch and fat, affect plasma metabolite profiles, milk production and fertility of dairy cows. Nutritional management before and after calving must
facilitate successful metabolic adaptations in the liver and rapid increases of postpartum DMI, indispensable for improved milk production and efficient reproductive performance. This review demonstrated that there are definite physiological and metabolic links between the amounts and types of dietary energy nutrients absorbed through the GIT of dairy cows and their biological responses such as milk secretion and reproduction outcomes. In particular, relationships between metabolic (e.g. glucose, amino acids, fatty acids) and endocrinologic (e.g. GH, insulin, IGF-I and leptin) signals and the reproductive system vary according to stage of the reproductive cycle. This suggests that the pregnancy rate could be optimized without compromising milk production with a two-diet strategy, consisting of a glucogenic diet until the resumption of the oestrous cycle and a lipogenic diet from the breeding period onwards. However, fertility before the establishment of oestrus in heifers or the resumption of oestrus in postpartum cows to the next calving is not only complex and multifactorial, but is in decline worldwide. In addition, bovine results on pre- and postpartum effects of energy sources and levels and their combinations on milk production and reproduction are limited under long-term field conditions. This is an area of research that requires detailed investigations.

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Conflict of Interest Declaration
The authors certify that they have no affiliations with any organization or entity with financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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