# Rapid Post-uterine Involution in Dairy Cows: Mechanisms, Dietary Strategies, and Impact on Postpartum Recovery

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## Abstract

The postpartum period in dairy cows is critical for reproductive success, with uterine involution playing a central role in returning the reproductive tract to its pre-pregnancy state. Rapid uterine involution is essential for improving reproductive performance and minimizing the risk of postpartum complications. This review explores the nutritional mechanisms that influence uterine involution, focusing on key dietary strategies to promote tissue repair and recovery. We examine the role of energy, protein, minerals, vitamins, and fatty acids in supporting uterine health and accelerating involution. Additionally, the interplay between gut health, oxidative stress, and hormonal regulation is discussed in the context of nutrient-driven recovery. Furthermore, we highlight the effects of dietary modifications on inflammation control, uterine muscle function, and immune response, all of which contribute to faster involution and improved fertility outcomes. By synthesizing current research, this review provides a comprehensive overview of how strategic nutritional interventions can optimize postpartum recovery, enhance uterine health, and improve overall reproductive efficiency in dairy cows.

**Keywords:** Cow, energy balance, fatty acids, minerals, postpartum recovery, reproductive health, trace elements, uterine involution

## Introduction

The postpartum period in dairy cows represents a critical phase that significantly influences reproductive success and herd productivity. Uterine involution, the process by which the uterus returns to its pre-pregnancy state, is vital for the cow's ability to conceive again. The efficiency of uterine involution is closely linked to fertility, with faster recovery leading to a higher likelihood of successful rebreeding [1]. Moreover, rapid uterine involution can reduce the risks of postpartum disorders such as metritis, retained placenta, and other uterine infections, which can delay recovery and negatively affect subsequent pregnancies [2]. Nutrition plays a central role in regulating the rate of uterine involution and ensuring reproductive success.

A balanced diet, consisting of adequate energy, protein, vitamins, minerals, and fatty acids, is essential for supporting uterine tissue repair and reducing inflammation during the postpartum phase. These nutrients not only contribute to the structural integrity of uterine cells but also help modulate immune responses to combat infections [3]. Moreover, they influence key metabolic pathways involved in tissue regeneration, enhancing the recovery process. Recent research highlights the significant role of optimal nutrition during the early postpartum phase when cows are most vulnerable to metabolic disturbances. Nutritional management during this time can promote rapid uterine recovery and improve the chances of successful rebreeding, benefiting overall herd productivity.

The novelty of this review lies in its comprehensive approach to understanding how nutrition-induced mechanisms accelerate uterine involution in dairy cows. While previous studies have investigated the effects of individual nutrients, this review integrates the collective impact of multiple dietary factors such as energy, protein, fatty acids, vitamins, minerals, and trace elements. Additionally, it explores emerging areas of research, such as the role of gut microbiota and microbial metabolites in uterine recovery. The study also introduces new insights into hormonal modulation through diet, providing novel strategies for improving postpartum recovery and enhancing reproductive performance in dairy cows.

## Energy Metabolism and Body Condition

### *Energy balance and recovery*

Energy balance is critical for early postpartum recovery, supporting metabolism and tissue repair. A positive energy balance encourages efficient recovery, while negative energy balance hinders uterine repair of cow [4], [5]. Ensuring adequate energy intake during early lactation helps restore uterine function, accelerating recovery and improving reproductive health, leading to better postpartum outcomes and faster recovery.

### *Negative energy balance and inflammation*

Negative energy balance increases lipolysis, releasing free fatty acids that can enhance inflammation. High inflammation delays uterine involution and recovery [6]. Proper energy intake helps prevent excessive inflammation, aiding uterine tissue repair. By reducing inflammation, uterine health improves, leading to faster postpartum recovery, more efficient tissue regeneration, and better reproductive health following calving.

### *Glucose availability and repair*

Glucose is essential for tissue repair during uterine involution. Adequate glucose levels support cellular regeneration, while insufficient glucose slows down tissue repair [7]. Low glucose availability can hinder uterine recovery of cow. Ensuring proper glucose intake postpartum accelerates tissue healing, supports uterine involution, and improves reproductive health, contributing to better fertility and faster postpartum recovery.

### *Energy-dense diets and recovery*

Energy-dense diets contribute to increased adiposity, providing stored energy for reproductive recovery. More fat reserves can support faster uterine involution [8]. However, excess fat may lead to metabolic issues like insulin resistance. A balanced energy-dense diet ensures efficient recovery, preventing excessive fat buildup while promoting faster uterine healing and better reproductive outcomes in cattle.

### *BCS and uterine involution*

Body condition score (BCS) reflects energy reserves, which significantly affect uterine involution. Cows with an optimal BCS experience faster uterine involution due to better energy availability [9]. Inadequate or excessive BCS delays recovery. Maintaining an ideal BCS supports quicker uterine involution, improving reproductive health and enhancing postpartum recovery, leading to better fertility outcomes of cows.

### *High-starch diets and energy*

High-starch diets provide readily available glucose to support uterine contractions and tissue repair of cows. These diets promote faster postpartum recovery by ensuring glucose availability for metabolic activities [7]. However, excessive starch intake may lead to digestive issues. A balanced high-starch diet helps speed uterine involution and supports metabolic processes without compromising digestive health.

### *Ketosis and uterine health*

Ketosis, caused by negative energy balance, leads to high ketone levels that impair uterine health. Ketosis reduces immune function, hindering uterine recovery and increasing infection risk [3]. Managing ketosis with appropriate energy supplementation helps reduce ketone production, support immune responses, and accelerate uterine tissue healing, enhancing overall reproductive health and postpartum uterine involution.

### *Weight maintenance and repair*

Maintaining body weight during early lactation ensures sufficient energy reserves for reproductive tissue repair. A stable weight supports uterine health by providing necessary nutrients for tissue recovery. Weight loss during early lactation can lead to nutrient deficiencies, delaying uterine involution and impairing reproductive outcomes [10]. Proper weight maintenance promotes faster uterine recovery and better fertility.

### *Energy-rich feeds and oxidative stress*

Energy-rich feeds provide antioxidants and nutrients that help reduce oxidative stress in the uterus. Oxidative stress can damage uterine tissues, slowing repair and hindering involution [11]. Providing energy-rich diets with antioxidants like vitamin E and selenium reduces oxidative damage, promoting faster uterine healing and more efficient involution, enhancing overall reproductive health.

### *Low energy intake and contraction*

Low energy intake reduces glucose and fatty acid availability, affecting uterine muscle contractility and tissue repair. Weak contractions delay uterine involution, prolonging recovery. Ensuring adequate energy intake postpartum supports strong uterine contractions, speeding the expulsion of uterine contents and promoting faster recovery. This improves reproductive health and reduces postpartum complications.

## Protein Metabolism and Uterine Repair

### *Protein and tissue regeneration*

Dietary protein supports postpartum tissue regeneration, providing essential building blocks for cell repair. Adequate protein intake accelerates uterine tissue healing and promotes efficient uterine involution [12], [13]. Low protein intake slows tissue repair, prolonging recovery. Ensuring sufficient dietary protein supports faster uterine repair, improves reproductive outcomes, and enhances overall postpartum recovery by promoting faster uterine involution and better fertility.

### *Amino acids and collagen*

Essential amino acids are critical for collagen synthesis, which is essential for uterine tissue repair. Collagen strengthens uterine tissue and supports structural integrity during involution [14], [15]. Adequate intake of essential amino acids facilitates collagen formation, aiding uterine repair. Deficiencies in amino acids may hinder collagen production, delaying uterine involution and impairing tissue recovery, reducing overall reproductive health.

### *Protein malnutrition and involution*

Protein malnutrition during the postpartum period leads to delayed uterine involution. Insufficient protein intake impairs tissue repair and immune function, prolonging recovery. Malnutrition increases the risk of complications like infections and uterine disorders [16]. Ensuring adequate protein intake is essential for timely uterine involution, enhancing recovery speed, and reducing the likelihood of postpartum complications, ultimately supporting better reproductive outcomes.

### *Protein-energy balance and recovery*

A balanced protein and energy ratio is essential for optimal uterine recovery. An adequate balance ensures efficient tissue repair and energy availability for metabolic processes. Imbalances, such as excessive protein or energy deficiency, can delay uterine involution. Ensuring proper protein-energy ratios supports faster uterine recovery and improves reproductive health, ultimately leading to improved fertility and reduced postpartum complications [17].

### *Rumen-protected amino acids*

Rumen-protected amino acids bypass ruminal degradation and provide directly available essential amino acids to support uterine function. These amino acids enhance protein metabolism, promoting faster uterine tissue regeneration [18]. Their use supports reproductive health, improves uterine repair, and accelerates involution by maintaining protein synthesis during postpartum recovery. They play a crucial role in reducing uterine inflammation and improving tissue repair.

### *Protein intake and uterine elasticity*

Higher dietary protein intake enhances uterine elasticity, facilitating quicker involution [13]. Adequate protein supports collagen and elastin production, which are essential for maintaining uterine tissue flexibility. Low protein intake can reduce uterine elasticity, impairing recovery and increasing the risk of uterine prolapse. A balanced diet rich in protein promotes faster tissue repair, improving uterine function and overall postpartum recovery.

### *Protein and uterine inflammation*

Protein intake can mediate uterine inflammation by supporting immune function and tissue repair. Adequate protein levels help modulate the inflammatory response during postpartum recovery, reducing tissue damage and promoting faster involution [15]. Protein malnutrition can lead to heightened inflammation, delaying uterine repair and impairing recovery. Ensuring sufficient protein intake supports the reduction of uterine inflammation and accelerates involution.

### *Methionine and uterine contraction*

Dietary methionine supports uterine muscle contraction by enhancing protein synthesis and cellular repair. It plays a role in reducing oxidative stress and improving uterine function during postpartum recovery [19]. Inadequate methionine intake can impair uterine muscle contractions, delaying involution and recovery. Sufficient methionine intake improves uterine contractility, enhancing involution and promoting faster postpartum recovery and improved fertility outcomes.

### *Lysine and immune support*

Lysine plays a vital role in supporting immune responses during uterine involution [20]. It aids in collagen synthesis, which is essential for uterine tissue repair, and supports the immune system to fight infections. Adequate lysine intake promotes faster uterine repair and reduces the risk of postpartum infections. Protein-rich diets with sufficient lysine intake help optimize immune responses during recovery.

### *Protein supplementation and hemorrhage*

Protein supplementation helps reduce the risk of postpartum hemorrhage by supporting uterine tissue repair and strengthening uterine muscle contractions. Adequate protein intake promotes faster uterine involution, reducing the risk of bleeding and improving recovery. Insufficient protein may impair uterine contraction and tissue regeneration, increasing the likelihood of hemorrhage. Protein supplementation is crucial for reducing postpartum hemorrhage risks and supporting reproductive health of cows.

## Mineral Supplementation and Uterine Health

### *Calcium and muscle contractility*

Calcium plays a crucial role in uterine muscle contraction during postpartum recovery. It helps to regulate the contractile function of uterine muscles, facilitating faster involution [21]. Adequate calcium levels support strong uterine contractions and tissue repair. Deficiency in calcium can impair uterine contractility, slowing down involution and prolonging recovery, ultimately affecting reproductive health and overall postpartum performance.

### *Phosphorus and energy metabolism*

Phosphorus is essential for energy metabolism, especially in tissue repair and recovery after calving. It aids in ATP production, which is necessary for cellular repair and metabolic functions [22]. Sufficient phosphorus levels support uterine repair by providing energy for the synthesis of proteins and cellular components. Phosphorus deficiency can slow down uterine involution, delaying postpartum recovery and reducing fertility.

### *Magnesium and muscle relaxation*

Magnesium is vital for smooth muscle relaxation in the uterus during postpartum recovery of cows. It helps regulate muscle tone and prevent excessive uterine contractions that could impair recovery. Magnesium supports uterine relaxation, facilitating involution and tissue repair [23]. A deficiency in magnesium can lead to muscle spasms or uterine tension, hindering involution and prolonging the postpartum recovery period.

### *Zinc and cellular repair*

Zinc plays an important role in cellular repair processes, particularly in regenerating uterine tissue after calving. It supports protein synthesis, DNA repair, and cell division, all of which are essential for uterine tissue regeneration [24]. Adequate zinc intake accelerates uterine involution by promoting tissue healing and reducing inflammation. Zinc deficiency can impair tissue repair, slowing down the recovery process.

### *Selenium and oxidative stress*

Selenium acts as a powerful antioxidant, reducing oxidative stress in uterine cells. Oxidative stress impairs tissue repair and slows uterine involution. By neutralizing free radicals, selenium protects uterine cells from oxidative damage, promoting faster tissue regeneration [25]. Adequate selenium levels support a healthier postpartum recovery and reduce the risk of complications such as uterine infections and delayed involution.

### *Manganese and tissue elasticity*

Manganese contributes to tissue elasticity by supporting collagen and proteoglycan synthesis, both vital for uterine tissue repair [26]. Collagen fibers provide structural integrity to the uterus during involution [27]. Adequate manganese intake enhances tissue elasticity, promoting faster and more effective uterine healing. Deficiency in manganese can reduce the flexibility of uterine tissues, impairing recovery and prolonging involution of cows.

### *Copper and immune modulation*

Copper plays a key role in modulating the immune system, which is essential for postpartum uterine health. It supports the production of immune cells that help fight infections and promote tissue repair. Adequate copper intake enhances immune responses, reducing the risk of uterine infections and supporting faster recovery [28]. Copper deficiency can impair immune function, increasing susceptibility to postpartum complications.

### *Iodine and endocrine function*

Iodine is essential for maintaining proper endocrine function, particularly thyroid health, which influences uterine health. Thyroid hormones regulate metabolic processes that support uterine involution and tissue repair [29]. Adequate iodine intake ensures optimal thyroid function, improving recovery speed and uterine health. Iodine deficiency can disrupt hormonal balance, delaying uterine involution and impairing postpartum recovery of cows.

### *Sulfur and structural integrity*

Sulfur contributes to the structural integrity of uterine proteins, such as collagen and elastin, which are vital for uterine tissue repair. Sulfur-containing compounds like sulfated glycosaminoglycans play an important role in maintaining the elasticity and strength of uterine tissue. Adequate sulfur intake supports faster uterine involution and tissue regeneration, while deficiency can impair structural integrity, slowing recovery.

### *Chromium and glucose balance*

Chromium helps regulate blood glucose levels by enhancing insulin sensitivity, which supports faster recovery and energy metabolism. Balanced glucose levels ensure adequate energy availability for uterine tissue repair and muscle contractions. Chromium supplementation can improve glucose metabolism during the postpartum period, promoting faster uterine involution [30]. Deficiency in chromium may impair glucose utilization, slowing recovery and prolonging involution of cows.

## Vitamin Requirements for Uterine Recovery

### *Vitamin A and regeneration*

Vitamin A is essential for enhancing uterine epithelial regeneration after calving. It promotes cell differentiation and epithelial tissue repair, crucial for uterine health [4]. Adequate vitamin A levels improve the regeneration of the uterine lining, helping restore normal function. Deficiency in vitamin A may impair tissue repair, slowing down the involution process and affecting reproductive health of cows.

### *Vitamin D and calcium absorption*

Vitamin D plays a key role in calcium absorption, which is vital for uterine contractions during postpartum recovery. It helps regulate calcium homeostasis, promoting strong and effective uterine contractions. Adequate vitamin D levels ensure optimal calcium levels, supporting uterine involution [31]. Deficiency in vitamin D can lead to poor calcium absorption, weakening uterine muscle contractions and delaying recovery.

### *Vitamin E and oxidative damage*

Vitamin E acts as a powerful antioxidant, reducing oxidative stress and damage to uterine cells during postpartum recovery. It helps neutralize free radicals that can impair tissue repair and prolong involution [32]. Adequate vitamin E intake supports faster tissue regeneration by protecting cells from oxidative damage. Vitamin E deficiency can slow down uterine recovery and increase infection risk of cows.

### *Vitamin C and collagen synthesis*

Vitamin C is crucial for collagen synthesis, which provides structural integrity and strength to the uterine tissues during involution [33]. Collagen is essential for uterine repair, and vitamin C supports its production. Sufficient vitamin C levels promote faster tissue healing and strengthen the uterus. Deficiency in vitamin C can impair collagen formation, hindering uterine recovery and involution in cows.

### *B-vitamins and cellular energy*

B-vitamins are essential for cellular energy production, particularly for uterine cells during recovery. These vitamins support metabolism and the production of ATP, which is necessary for uterine muscle contractions and tissue repair [34]. Adequate B-vitamin intake ensures that uterine cells have the energy needed for regeneration. Deficiency in B-vitamins can slow uterine involution and reduce tissue repair efficiency.

### *Vitamin K and bleeding*

Vitamin K plays a vital role in blood coagulation and minimizing postpartum bleeding complications. It supports the synthesis of clotting factors that prevent excessive hemorrhage after calving [35]. Adequate vitamin K intake helps control bleeding, facilitating faster uterine healing. Deficiency in vitamin K may increase the risk of hemorrhage, delaying uterine recovery and prolonging the involution process.

### *Folic acid and cell division*

Folic acid is essential for cell division and tissue repair, supporting the regeneration of uterine cells during postpartum recovery [36]. It aids in DNA synthesis, crucial for cellular regeneration and uterine healing. Sufficient folic acid intake accelerates tissue repair and promotes faster uterine involution. Deficiency in folic acid can impair cell division, delaying recovery and tissue regeneration in cows.

### *Thiamine and ATP production*

Thiamine is crucial for ATP production, providing the necessary energy for uterine muscle contractions during postpartum recovery. Adequate thiamine levels support the metabolism of carbohydrates and facilitate efficient energy use for uterine tissue repair [37]. Thiamine deficiency can reduce ATP production, weakening uterine contractions and slowing involution. Maintaining proper thiamine levels ensures effective uterine function and faster recovery.

### *Riboflavin and antioxidant defense*

Riboflavin plays a role in cellular antioxidant defense, protecting uterine cells from oxidative stress during postpartum recovery. It aids in the regeneration of antioxidants like glutathione, which neutralizes free radicals and reduces cellular damage [38]. Sufficient riboflavin intake supports uterine healing by protecting cells. Deficiency in riboflavin can increase oxidative damage, slowing uterine involution and delaying recovery.

### *Biotin and cellular repair*

Biotin contributes to cellular repair and regeneration by supporting the metabolism of fatty acids and amino acids in uterine cells [39]. It promotes healthy cell division and tissue healing, accelerating uterine involution. Adequate biotin intake ensures that uterine cells regenerate efficiently. Biotin deficiency can impair cellular repair, hindering the recovery process and delaying uterine tissue regeneration during postpartum in cows.

## Fatty Acids and Inflammatory Modulation

### *Omega-3 and inflammation*

Omega-3 fatty acids play a key role in reducing uterine inflammation postpartum. They inhibit the production of pro-inflammatory cytokines and prostaglandins, promoting a more favorable inflammatory response [40]. Omega-3 supplementation supports uterine tissue repair and accelerates involution by reducing inflammation. Adequate omega-3 levels improve overall uterine health, enhancing recovery and minimizing the risk of infection during postpartum.

### *CLA and immune response*

Conjugated linoleic acid (CLA) positively influences immune responses, helping to reduce inflammation in the uterus. It enhances the production of anti-inflammatory cytokines and modulates the immune system [41]. CLA supplementation supports uterine health by improving immune function and reducing the risk of infections. CLA also aids in faster uterine tissue repair, contributing to optimal reproductive recovery in cows.

### *Omega-6 to omega-3 balance*

The balance between omega-6 and omega-3 fatty acids is crucial for prostaglandin synthesis, which regulates uterine contractions and inflammation [42]. A high omega-6 to omega-3 ratio may promote pro-inflammatory prostaglandins, hindering uterine recovery. Achieving an optimal balance of these fatty acids helps control inflammation and supports efficient uterine involution, enhancing tissue repair and reproductive health.

### *EPA and DHA effects*

Eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), both omega-3 fatty acids, reduce oxidative stress and inflammation in uterine tissues. They neutralize free radicals, protecting cells from oxidative damage and promoting faster tissue repair. Supplementation with EPA and DHA enhances uterine recovery by reducing oxidative stress, improving tissue integrity, and speeding up the involution process postpartum [43].

### *PUFA supplementation and recovery*

Polyunsaturated fatty acids (PUFAs), particularly omega-3 and omega-6, play a vital role in uterine cell recovery. PUFA supplementation enhances cell membrane fluidity, supports tissue regeneration, and reduces inflammation. PUFAs contribute to faster uterine involution and improve reproductive health [44]. Balanced PUFA intake helps optimize uterine function and repair, preventing delays in recovery and enhancing postpartum outcomes.

### *Fatty acids and cytokine response*

Fatty acids modulate uterine cytokine responses by influencing the production of pro-inflammatory and anti-inflammatory cytokines. Omega-3 fatty acids, in particular, shift cytokine production toward anti-inflammatory pathways, enhancing tissue healing [45]. This modulation of cytokine responses by fatty acids reduces uterine inflammation, supporting faster involution and improving uterine function during postpartum recovery and future reproductive health in cows.

### *Linoleic acid and hormonal regulation*

Linoleic acid, an essential omega-6 fatty acid, plays a role in hormonal regulation during the postpartum period. It helps regulate the synthesis of prostaglandins, which control uterine contractions [46]. Proper linoleic acid levels contribute to balanced hormonal responses, aiding in uterine repair and reducing inflammation. Imbalanced linoleic acid intake can disrupt hormonal regulation, slowing down uterine recovery.

### *DHA and muscle tone*

Docosahexaenoic acid (DHA) enhances uterine muscle tone by supporting cell membrane integrity and improving uterine contractions. DHA supplementation during the postpartum period helps maintain muscle function, supporting effective uterine involution. Adequate DHA levels facilitate strong contractions, promoting faster expulsion of uterine contents and faster recovery. DHA also reduces oxidative stress, further enhancing uterine muscle tone and repair.

### *Fat supplementation and tissue health*

Fat supplementation, particularly with omega-3 fatty acids, supports reproductive tissue health by improving cell membrane function and reducing inflammation [47]. Adequate fat intake enhances tissue integrity, accelerates uterine involution, and promotes faster recovery. Fatty acids also support hormone production necessary for uterine repair [48]. Imbalanced fat supplementation can hinder recovery, emphasizing the importance of proper fat intake for uterine health in cows.

### *Trans-fatty acids and inflammation*

Trans-fatty acids, often present in processed foods, can increase uterine inflammation and impair tissue repair during postpartum recovery. These fats contribute to the production of pro-inflammatory cytokines, delaying uterine involution and promoting oxidative stress. Limiting trans-fatty acid intake during the postpartum period helps reduce inflammation, supports efficient tissue repair, and accelerates uterine recovery, promoting better reproductive outcomes in cows [49].

## Antioxidant Support and Immune Function

### *Antioxidant feeds and uterine protection*

Antioxidant-rich feeds, including those containing vitamin E, selenium, and polyphenols, protect uterine cells from oxidative stress. These antioxidants neutralize free radicals, reducing cellular damage and supporting uterine health [50]. By mitigating oxidative stress, antioxidant-rich diets enhance tissue repair, accelerate uterine involution, and improve immune function, promoting overall reproductive health and reducing inflammation postpartum.

### *Selenium and vitamin E*

Selenium and vitamin E are essential antioxidants that modulate immune responses and reduce inflammation in uterine tissues [51]. They protect uterine cells from oxidative damage, supporting tissue regeneration during postpartum recovery. Selenium enhances immune function, while vitamin E prevents cellular damage, ensuring faster uterine involution [52]. Together, they improve reproductive health and accelerate the healing process postpartum in cows.

### *Polyphenols and oxidative damage*

Polyphenols, found in fruits and vegetables, are powerful antioxidants that help reduce oxidative damage in uterine tissues [53]. They neutralize free radicals, minimizing tissue damage during postpartum recovery. Polyphenols also enhance the immune response, promoting faster uterine involution [54]. By modulating inflammation and reducing oxidative stress, polyphenol-rich diets support efficient tissue repair and enhance overall uterine health in cows.

### *Carotenoids and cell stability*

Carotenoids, such as beta-carotene, support uterine epithelial cell stability by reducing oxidative stress and promoting cell regeneration. These antioxidants protect the cells from free radical damage, enhancing tissue repair during the postpartum period [55]. Carotenoids also contribute to immune system modulation, reducing inflammation and supporting uterine health. Adequate carotenoid intake accelerates uterine involution and recovery.

### *Flavonoids and inflammation control*

Flavonoids, plant-derived compounds found in fruits, vegetables, and herbs, possess strong anti-inflammatory properties that help control inflammation in the uterus [56]. They modulate cytokine production, reducing the release of pro-inflammatory molecules and promoting uterine tissue healing. By enhancing the anti-inflammatory response, flavonoids help improve uterine health, support faster recovery, and optimize reproductive function postpartum.

### *Resveratrol and cellular repair*

Resveratrol, a polyphenolic compound found in grapes and berries, accelerates cellular repair in uterine tissues by enhancing antioxidant activity and reducing inflammation [57]. It protects uterine cells from oxidative damage, supports immune function, and promotes faster tissue regeneration. Resveratrol supplementation during the postpartum period helps improve uterine health, speeds up involution, and supports overall reproductive recovery in cows.

### *Lutein and oxidative prevention*

Lutein, a carotenoid antioxidant, helps prevent oxidative damage in uterine cells by neutralizing free radicals and supporting cellular health. It contributes to the stability of uterine epithelial cells, reducing inflammation and enhancing tissue repair [50]. Lutein supplementation promotes faster uterine involution by protecting cells from oxidative stress, ensuring efficient recovery and improving reproductive health during the postpartum period.

### *Antioxidant enzymes and uterine health*

Antioxidant enzymes, including superoxide dismutase and catalase, play a crucial role in maintaining uterine health by neutralizing harmful reactive oxygen species [50], [58]. These enzymes help reduce oxidative stress in uterine tissues, supporting faster involution and tissue repair. Enhanced antioxidant enzyme activity strengthens uterine recovery, minimizes inflammation, and supports overall immune function, promoting reproductive health postpartum.

### *Phytochemicals and inflammation*

Phytochemicals, naturally occurring compounds found in plants, help modulate inflammation and support uterine health. These compounds possess antioxidant, anti-inflammatory, and immune-modulating properties that enhance uterine recovery during postpartum. By reducing oxidative stress and inflammatory responses, phytochemicals promote faster uterine involution and contribute to overall reproductive health, ensuring effective tissue repair and improved immune function in cows [59].

### *Melatonin and antioxidant protection*

Melatonin, a hormone with antioxidant properties, plays a vital role in protecting uterine cells from oxidative damage. It enhances the activity of antioxidant enzymes and reduces free radical production in uterine tissues [60]. Melatonin supplementation during the postpartum period helps reduce inflammation, improve immune function, and promote faster uterine involution, supporting overall reproductive health and recovery in cows.

## Hormonal Modulation via Nutrition

### *Diet and estrogen levels*

Diet plays a significant role in modulating estrogen levels postpartum, influencing uterine health. Nutrient intake, including fats and proteins, affects estrogen production and regulation. Adequate energy, protein, and micronutrient supply support optimal estrogen levels, promoting uterine tissue repair and faster involution [61], [62]. Nutrient imbalances can disrupt estrogen synthesis, leading to delayed uterine recovery and impaired reproductive function.

### *Insulin sensitivity and contractions*

Insulin sensitivity influences uterine contractions by modulating energy metabolism. Diets that improve insulin sensitivity promote efficient glucose utilization, supporting stronger uterine contractions during involution. Insulin resistance, often exacerbated by high-fat diets, can hinder uterine muscle function, delaying involution [63]. Maintaining insulin sensitivity through proper nutrition optimizes uterine contractility, accelerating recovery and improving postpartum reproductive outcomes in cows.

### *Glucose regulation and prolactin*

Glucose regulation directly impacts prolactin levels, which influence milk production and uterine involution. Stable blood glucose levels promote optimal prolactin secretion, supporting uterine tissue repair and lactation [7]. High glucose variability can interfere with prolactin synthesis, impairing uterine recovery and milk yield. Diets that stabilize glucose levels enhance prolactin regulation, contributing to improved reproductive health and efficient recovery postpartum in cows.

### *Fatty acids and prostaglandins*

Dietary fatty acids, particularly omega-3 and omega-6, affect prostaglandin production, which regulates uterine contractions and inflammation. Omega-3 fatty acids reduce pro-inflammatory prostaglandins, promoting uterine health and speeding up involution [43]. A balanced intake of these fatty acids ensures proper prostaglandin synthesis, aiding uterine tissue repair. An imbalance in fatty acid intake can negatively affect uterine function and recovery.

### *Oxytocin release and diet*

Diet influences oxytocin release, a key hormone responsible for uterine contractions and milk ejection. Nutrients such as fats and proteins support optimal oxytocin secretion by regulating hormonal pathways. Balanced nutrition enhances oxytocin's role in uterine involution, promoting faster recovery [64]. Insufficient nutrient intake can hinder oxytocin release, delaying uterine contractions and prolonging the recovery process postpartum.

### *IGF and uterine repair*

Insulin-like growth factor (IGF) plays a critical role in tissue repair, including uterine recovery [65], [66]. Adequate nutrition, particularly protein and energy intake, promotes IGF production, facilitating cellular repair and regeneration in uterine tissues. A well-balanced diet supports IGF regulation, enhancing uterine tissue repair during postpartum involution. Nutritional deficiencies can reduce IGF levels, impairing uterine healing and recovery.

### *Thyroxine and metabolic recovery*

Thyroxine, a thyroid hormone, is essential for metabolic regulation during postpartum recovery [67]. Proper nutrition supports thyroid function, ensuring adequate thyroxine levels. Balanced energy intake, particularly from carbohydrates and fats, optimizes thyroid hormone production, promoting efficient metabolic recovery [68]. Nutrient deficiencies can impair thyroxine synthesis, hindering metabolic processes and slowing uterine involution and overall postpartum recovery.

### *Diet and cortisol regulation*

Diet modulates cortisol levels, a hormone involved in stress responses and uterine recovery. Proper nutrition supports cortisol regulation, reducing excessive stress and inflammation during postpartum recovery [69]. Diets rich in antioxidants and essential fatty acids can mitigate cortisol's negative effects on uterine health. Chronic high cortisol levels due to poor nutrition can delay uterine involution and hinder recovery.

### *Leptin modulation and repair*

Leptin, a hormone involved in energy balance and reproductive function, is influenced by dietary intake. Diets that regulate leptin levels optimize uterine repair by promoting energy availability for tissue regeneration [70]. Leptin modulates the reproductive system, influencing recovery processes. Nutritional imbalances can disrupt leptin signaling, slowing uterine involution and impairing tissue regeneration during the postpartum period.

### *FSH and LH modulation*

Diet-induced modulation of follicle-stimulating hormone (FSH) and luteinizing hormone (LH) levels influences ovarian function and reproductive recovery [71]. Balanced nutrition supports optimal FSH and LH secretion, which are essential for the regulation of the estrous cycle and uterine healing [10]. Nutrient deficiencies can disrupt the hormonal balance, delaying recovery and impacting reproductive function during the postpartum period.

## Microbial Balance and Gut-Uterine Axis

### *Probiotics and immune response*

Probiotics influence uterine immune responses by enhancing the gut's microbiota, which in turn improves the immune system’s ability to combat infections. By balancing microbial populations in the gut, probiotics can promote a more favorable uterine environment, supporting faster recovery from postpartum inflammation and reducing the risk of uterine infections, ultimately promoting efficient uterine involution [72].

### *Prebiotics and microbiota health*

Prebiotics, by nourishing beneficial gut bacteria, positively impact uterine health. They support the growth of beneficial microbes, which enhance gut integrity and immune responses. Improved gut health through prebiotic supplementation can lead to reduced systemic inflammation and improved uterine tissue repair, thereby accelerating postpartum recovery and contributing to better uterine health and overall reproductive function.

### *Gut microbiota and inflammation*

Gut microbiota plays a critical role in modulating systemic inflammation, which affects uterine health. A balanced microbiome helps regulate inflammatory cytokines, reducing excessive inflammation in the uterus [73]. Dysbiosis, or an imbalance in gut microbes, can lead to chronic inflammation, impairing uterine repair. Maintaining gut health is essential for controlling inflammation and supporting uterine tissue regeneration after calving.

### *SCFA and uterine contraction*

Short-chain fatty acids (SCFAs), produced by gut bacteria from fiber fermentation, influence uterine contractions and recovery [74]. SCFAs such as acetate and butyrate promote smooth muscle function, enhancing uterine contractility. Proper uterine contractions are necessary for expelling uterine contents and facilitating rapid involution. SCFAs also reduce inflammation, supporting overall uterine health and recovery postpartum by improving muscle tone and tissue repair.

### *Fiber and cytokine signaling*

Dietary fiber influences gut-uterine cytokine signaling by promoting the production of beneficial short-chain fatty acids (SCFAs) [75]. These SCFAs can modulate immune responses and reduce uterine inflammation. Fiber intake supports a balanced gut microbiota, which enhances the production of anti-inflammatory cytokines [76]. This promotes quicker uterine healing and helps regulate the inflammatory processes involved in postpartum uterine involution.

### *Yeast culture and immune response*

Yeast culture supplementation positively influences the immune response in uterine cells by improving gut microbial balance. The metabolites produced by yeast culture support the activation of immune cells and enhance gut barrier function [77]. By modulating immune responses, yeast cultures help reduce inflammation, support uterine tissue repair, and promote faster recovery from postpartum uterine infections, improving reproductive health.

### *Microbial diversity and recovery*

Gut microbial diversity plays a crucial role in postpartum recovery by supporting overall immune function and reducing systemic inflammation [72]. A diverse microbiome is associated with improved immune responses, which enhance uterine tissue repair and involution. Maintaining microbial diversity through diet and supplementation promotes a balanced immune system, reducing infection risk and accelerating recovery during the postpartum period.

### *Gut-derived metabolites and uterine health*

Gut-derived metabolites, particularly short-chain fatty acids (SCFAs), signal uterine health by modulating inflammation and promoting tissue repair. SCFAs influence gene expression in uterine cells, enhancing their ability to regenerate and contract. These metabolites also reduce oxidative stress and improve immune responses, contributing to faster uterine involution and reducing the likelihood of postpartum complications such as infections.

### *Microbiome and nutrient absorption*

The gut microbiome is vital for nutrient absorption, which directly influences uterine repair and recovery. A balanced microbiome enhances the absorption of essential nutrients such as glucose, amino acids, and fatty acids, which are required for tissue regeneration and uterine function [78]. Improving gut health can support more efficient nutrient utilization, promoting faster uterine involution and improving overall reproductive outcomes.

### *SCFAs and inflammation reduction*

Short-chain fatty acids (SCFAs) produced by gut bacteria play an important role in reducing inflammation, particularly in the uterus. SCFAs such as acetate, propionate, and butyrate act as anti-inflammatory agents, regulating immune cell function and cytokine production [79], [80]. SCFAs promote uterine health by minimizing inflammation, supporting tissue repair, and enhancing the overall recovery process during the postpartum period.

## Lipid Metabolism and Endometrial Recovery

### *Fat-soluble vitamins and uterine repair*

Fat-soluble vitamins such as A, D, E, and K play key roles in uterine repair by supporting tissue regeneration and immune function [81]. Vitamin A aids epithelial tissue regeneration, while vitamin E acts as an antioxidant, protecting uterine cells from oxidative stress [51]. Vitamin D supports calcium metabolism, essential for uterine contractions, and vitamin K contributes to blood coagulation, preventing postpartum hemorrhage.

### *Fatty acids and cellular structure*

Fatty acids influence endometrial cellular structure by affecting membrane fluidity, stability, and functionality. Omega-3 and omega-6 fatty acids, in particular, play roles in regulating inflammation and cellular repair [82]. These essential fatty acids support the formation of phospholipids in cell membranes, enhancing cell signaling and recovery processes, which ultimately aids in efficient uterine tissue repair during postpartum recovery.

### *Cholesterol metabolism and hormones*

Cholesterol metabolism is vital for the synthesis of steroid hormones, including estrogen and progesterone, which regulate uterine function. These hormones control endometrial cell proliferation and differentiation, essential for uterine tissue repair. Dysregulation of cholesterol metabolism can impair hormonal synthesis, hindering uterine recovery. Proper lipid metabolism supports optimal hormone levels, improving uterine involution and reproductive function postpartum.

### *Lipid peroxidation control*

Lipid peroxidation refers to the oxidative degradation of lipids, which can damage cellular membranes and impair uterine function [58]. Controlling lipid peroxidation through antioxidant supplementation, such as vitamin E, protects uterine cells from oxidative stress [51]. By reducing oxidative damage, lipid peroxidation control supports the repair of endometrial tissue, promoting faster recovery and minimizing inflammation, contributing to better postpartum uterine health.

### *Lipoproteins and nutrient transport*

Lipoproteins are essential for transporting lipids and fat-soluble vitamins to uterine cells, supporting tissue repair and energy supply. They help to maintain the integrity of uterine cell membranes, facilitate nutrient uptake, and regulate lipid metabolism during the postpartum period [83]. Adequate lipoprotein levels are crucial for providing essential fatty acids and vitamins to uterine tissues, accelerating endometrial recovery and promoting uterine health.

### *Medium-chain triglycerides and uterine health*

Medium-chain triglycerides (MCTs) are rapidly absorbed and metabolized, providing quick energy for uterine cells during recovery. MCTs are utilized more efficiently than long-chain fatty acids, promoting faster uterine tissue regeneration and reducing recovery time.

Additionally, MCTs support immune function, which can help reduce the risk of uterine infections postpartum, further supporting overall uterine health and recovery [49].

### *Adipokines and uterine contractility*

Adipokines, hormones secreted by adipose tissue, play a role in modulating uterine contractility and inflammation. Adiponectin, for example, has anti-inflammatory properties and supports uterine muscle function [84]. Conversely, leptin and resistin can promote inflammation and impair uterine contractility [85]. The balance of adipokines influences the effectiveness of uterine contractions and the overall recovery process during the postpartum period, affecting uterine involution speed.

### *Dietary lipids and uterine energy*

Dietary lipids provide a concentrated source of energy for uterine cells during recovery. Lipids, particularly essential fatty acids, support the regeneration of uterine tissues, enhance cellular function, and improve the overall efficiency of uterine involution [86]. Adequate intake of dietary lipids ensures sufficient energy availability for metabolic processes, facilitating faster tissue repair and optimal uterine recovery postpartum.

### *Lipid profile and inflammation*

A balanced lipid profile, particularly with a proper ratio of omega-3 to omega-6 fatty acids, is crucial for controlling inflammation in the uterus. Dysregulated lipid profiles, with high levels of pro-inflammatory fatty acids, can increase uterine inflammation and delay recovery [87]. A favorable lipid profile helps regulate inflammatory markers, reducing tissue damage and promoting efficient uterine involution and postpartum recovery.

### *Fat digestion efficiency*

The efficiency of fat digestion influences nutrient absorption and uterine tissue repair. Improved fat digestion leads to better absorption of essential fatty acids, which are required for cellular repair and energy supply during uterine involution [88]. Adequate fat digestion supports the delivery of critical nutrients to the uterus, promoting faster recovery, reducing inflammation, and enhancing overall postpartum uterine health and tissue regeneration.

## Trace Elements and Enzyme Activity in Uterine Involution

### *Molybdenum and enzymatic processes*

Molybdenum plays a crucial role in enzymatic processes within uterine cells by acting as a cofactor for enzymes involved in sulfur metabolism and detoxification [89]. These enzymatic activities are essential for uterine tissue repair during postpartum involution. Adequate molybdenum levels support metabolic processes that contribute to faster recovery and proper uterine function, promoting efficient tissue regeneration after calving.

### *Boron and tissue repair*

Boron contributes to tissue repair by influencing mineral metabolism and enhancing the activity of enzymes involved in collagen synthesis [90]. This trace element also supports the structural integrity of uterine tissues by stabilizing bone and mineral homeostasis. Adequate boron levels improve the synthesis of important extracellular matrix proteins, promoting uterine tissue repair and accelerating postpartum recovery.

### *Cobalt and uterine health*

Cobalt is an essential trace element that supports uterine health by being a key component of vitamin B12, which is involved in cell division and tissue repair [89]. It plays a role in erythropoiesis, enhancing blood oxygenation during the postpartum period. Adequate cobalt levels ensure optimal uterine function by promoting cellular repair, immune responses, and metabolic recovery.

### *Fluoride and collagen synthesis*

Fluoride is involved in collagen synthesis and the mineralization of uterine tissue [91]. It enhances the structural integrity of the endometrial matrix, crucial for uterine repair and recovery after calving. By supporting collagen formation, fluoride helps maintain tissue elasticity and strength, aiding uterine involution and improving the overall structural recovery of the uterine lining during postpartum recovery.

### *Nickel and enzyme activity*

Nickel influences enzyme activity that is crucial for uterine repair by participating in the regulation of various metabolic processes. It supports cellular enzyme activity involved in tissue regeneration, collagen synthesis, and energy production [92]. By optimizing enzyme function, nickel contributes to the efficient repair of uterine tissues, ensuring smooth uterine involution and promoting faster postpartum recovery.

### *Iron and uterine blood flow*

Iron plays a significant role in supporting uterine blood flow and oxygenation during postpartum recovery. As a key component of hemoglobin, iron facilitates oxygen transport to uterine tissues, promoting cell regeneration and repair. Adequate iron levels are essential for optimal uterine function, as they ensure proper blood circulation and oxygen supply, enhancing uterine tissue repair and involution.

### *Trace element bioavailability and recovery*

Bioavailability of trace elements is critical for effective uterine tissue recovery. Proper absorption of minerals like molybdenum, cobalt, and iron ensures they can participate in enzymatic and metabolic processes essential for uterine involution [93]. Inadequate bioavailability of these trace elements can impair tissue repair and slow down the recovery process, emphasizing the importance of balanced mineral intake for postpartum health.

### *Dietary nickel and muscle tone*

Dietary nickel influences uterine muscle tone during postpartum recovery. It helps regulate enzyme systems that affect uterine muscle function and contraction [94]. By supporting proper muscle tone, nickel contributes to efficient uterine involution, helping to expel uterine contents and reduce the risk of complications like retained placenta or infection. Adequate nickel intake aids in restoring uterine muscle health postpartum.

### *Trace element synergies and involution*

The synergies between various trace elements, such as zinc, copper, and selenium, play a pivotal role in promoting rapid uterine involution [93]. These minerals work together to optimize enzymatic function, collagen synthesis, and immune responses during the postpartum period. Ensuring a balanced intake of trace elements accelerates uterine recovery, minimizing inflammation and enhancing the efficiency of uterine tissue repair.

### *Mineral chelation and enzyme support*

Mineral chelation enhances enzyme support for uterine tissue health by improving the bioavailability of trace elements required for enzymatic processes [95]. Chelated minerals are more readily absorbed and utilized by uterine cells, promoting efficient metabolic activity and tissue regeneration. This process is crucial for supporting uterine repair, as it ensures optimal enzyme function, accelerating recovery and reducing inflammation in uterine tissues.

## Nutrient-Driven Molecular Pathways for Tissue Repair

### *mTOR pathway and cell proliferation*

The mTOR pathway plays a crucial role in uterine cell proliferation by regulating protein synthesis and cell growth [96]. Nutrient availability, particularly amino acids, activates this pathway, promoting cellular regeneration and tissue repair [97]. Activation of mTOR supports the growth of uterine cells during postpartum recovery, accelerating uterine involution and improving reproductive health by enhancing tissue regeneration.

### *NF-kB and inflammation control*

NF-kB is a critical regulator of inflammation, and its modulation is essential for controlling uterine inflammation during recovery. Nutrient-driven regulation of NF-kB can reduce the inflammatory response, promoting faster uterine tissue repair [98]. By suppressing excessive inflammation, the NF-kB pathway supports the healing process, accelerating uterine involution and improving reproductive outcomes in postpartum cows.

### *Insulin signaling and muscle repair*

Insulin signaling plays a vital role in uterine muscle cell repair by promoting glucose uptake and protein synthesis [65]. Adequate insulin signaling ensures proper energy availability for tissue regeneration. Insulin regulates growth factors involved in cellular repair processes, helping restore uterine muscle tissue post-calving. Proper insulin function accelerates uterine repair and promotes efficient involution during the postpartum period [99].

### *AMPK activation and energy efficiency*

AMPK activation promotes cellular energy efficiency by enhancing glucose uptake and fatty acid oxidation, essential for uterine tissue repair [100]. During the postpartum period, AMPK helps maintain energy homeostasis, ensuring that uterine cells receive adequate nutrients for regeneration. This activation supports efficient uterine involution, reduces cellular stress, and enhances recovery by optimizing energy utilization for tissue repair.

### *Antioxidant pathways and oxidative damage*

Antioxidant pathways play a critical role in protecting uterine cells from oxidative damage, which can impair tissue repair [50]. Nutrients like vitamin E and selenium activate these pathways, reducing oxidative stress in the uterus. By mitigating free radical damage, antioxidant pathways support cellular stability, accelerate uterine tissue regeneration, and contribute to overall uterine health and efficient involution postpartum.

### *IGF-1 pathway and regeneration*

The IGF-1 pathway is integral to uterine cellular regeneration by stimulating cell growth and division. Insulin-like growth factor 1 (IGF-1) promotes tissue repair by enhancing protein synthesis and cellular proliferation in the uterus [101]. Nutrients like amino acids and glucose activate this pathway, accelerating uterine tissue recovery, improving uterine health, and enhancing the efficiency of postpartum uterine involution.

### *Autophagy regulation and tissue recovery*

Autophagy regulation plays a key role in uterine tissue recovery by facilitating the removal of damaged cellular components and promoting cell survival [102]. Nutrients like amino acids can modulate autophagy, enhancing the repair of uterine tissues during postpartum recovery. By supporting the recycling of cellular material, autophagy accelerates tissue regeneration, leading to faster uterine involution and improved postpartum health.

### *PI3K/AKT pathway and repair*

The PI3K/AKT pathway is crucial in promoting uterine repair by regulating cell survival, growth, and metabolism. Nutrient availability, particularly amino acids and lipids, activates this pathway, enhancing uterine tissue regeneration and preventing cellular apoptosis [3]. This signaling pathway promotes efficient uterine involution, supports the repair of damaged tissues, and contributes to faster postpartum recovery and reproductive health.

### *JAK-STAT pathway and cytokine signaling*

The JAK-STAT pathway plays a central role in uterine inflammation and immune responses, regulating cytokine signaling during postpartum recovery [103]. Nutrients influence the activation of this pathway, modulating immune responses and promoting tissue repair. By controlling inflammation and supporting immune function, the JAK-STAT pathway accelerates uterine involution, enhances tissue regeneration, and supports the overall postpartum recovery process.

### *HIF-1 pathway and oxygen delivery*

The HIF-1 pathway is essential for regulating oxygen delivery to uterine cells during recovery. Nutrient-driven regulation of HIF-1 helps optimize oxygen utilization, promoting cellular survival and tissue repair under low-oxygen conditions [104]. By improving uterine oxygenation, the HIF-1 pathway enhances the recovery of uterine tissues, accelerates involution, and supports the efficient healing of uterine cells post-calving.

## Future directions

Future research should focus on refining dietary strategies that optimize uterine involution without compromising metabolic health and lactation performance. Identifying precise nutrient compositions, including energy-protein ratios, micronutrient fortification, and functional feed additives, will be critical in accelerating uterine repair. The role of bioactive compounds such as omega-3 fatty acids, polyphenols, and probiotics in modulating inflammatory responses and enhancing tissue regeneration warrants further investigation. Advanced metabolomics and transcriptomics should be integrated to elucidate molecular pathways linking nutrition with uterine recovery dynamics. The gut-reproductive axis presents an emerging area for exploration, particularly in understanding how gut microbiota and their metabolites influence uterine healing. Additionally, evaluating breed-specific responses to tailored nutritional interventions can enhance precision feeding strategies for diverse dairy systems. Longitudinal studies assessing the carryover effects of transition diets on subsequent reproductive efficiency will provide insights into sustainable postpartum management. Innovative feeding technologies, such as slow-release nutrient formulations and precision supplementation, should be explored for their role in optimizing nutrient utilization and uterine health. Collaborative research bridging veterinary, nutritional, and reproductive sciences is essential to develop holistic strategies that improve postpartum recovery while maintaining productivity and welfare standards in dairy farming.

## Conclusion

Nutrition plays a crucial role in supporting rapid uterine involution and promoting postpartum recovery in dairy cows. A well-balanced diet that includes adequate energy, protein, vitamins, minerals, and fatty acids is essential for optimal uterine health and fertility. By influencing key metabolic pathways and immune functions, proper nutrition accelerates the recovery of uterine tissue and reduces the risk of postpartum disorders. Emerging research highlights the potential for integrating gut microbiota and hormonal modulation into nutritional strategies, offering novel avenues to enhance uterine health. Overall, this review underscores the importance of nutrition in ensuring efficient uterine involution and improving reproductive performance in dairy cows.

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