Insulin-Mimetic Properties and Bioactive Mechanisms of Camel Milk Proteins: A Comparative Review with Bovine Insulin

Amina Hussein Jimale

Degree project/Independent project • 15 credits
Swedish University of Agricultural Science, SLU
Department of Molecular Science
Bachelor Programme – Food Science
Molecular Sciences, 2026:06
Uppsala, 2026

Insulin-Mimetic Properties and Bioactive Mechanisms of Camel Milk Proteins: A Comparative Review with Bovine Insulin

Amina Hussein Jimale

Supervisor:	**Saeid Karkehabadi, SLU, Department of Molecular Science**
Examiner:	Santanu Basu, SLU, Department of Molecular Science

Credits:	15
Level:	G2E
Course title:	Bachelor Thesis in Food Science, G2E
Course code:	EX0876
Programme/education:	Bachelor Programme in Food Science
Place of publication:	Uppsala
Year of publication:	2026
Title of series:	Molecular Sciences
Part number:	2026:06

Keywords: Camel milk, proteins, Bovine insulin, diabetes, blood sugar control, bioactive compounds,

Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agriculture Science (NJ)
Department of Molecular Science

Abstract

Camel milk has attracted growing scientific interest because of its health benefits, especially in relation to diabetes and blood sugar control. This review focused on the gastric stability of camel milk proteins and the insulin-mimetic activity of its peptides that is generated during digestion in comparison to bovine milk. Camel milk is a nutrition-rich source that naturally contains vitamins, minerals, insulin and insulin-like compounds. It differs structurally from bovine milk with its higher proportion of β-casein, lower amounts of αs1-casein and the near absence of β-lactoglobulin. The results demonstrate that camel milk is digested differently from bovine milk which may preserve the function of its bioactive peptides. Camel milk peptides have shown to inhibit carbohydrate-related enzymes and DPP-IV, as well as stimulating insulin related pathways that are linked to AKT activation and GLUT4 mediated glucose uptake. *In vivo* studies showed regained metabolic balance after camel milk therapy. However, despite promising *in vitro* and *in vivo* studies, the lack of large-scale human studies remains a major limitation.

Table of contents

List of tables **4**

1. Introduction **5**

2. Method **6**

3. Results **6**

3.1 Structural composition of camel milk proteins 6

3.1.1. Casein & Whey: Unique ration and lack of B-lactoglubulin 7

3.1.2. Insulin and Insulin-like proteins 8

3.1.3. Protective molecules: Lactoferrin and immunoglobulin 8

3.2 Gastric stability 9

3.2.1. Proteolytic resistance 9

3.2.1.1 Casein digestion 9

3.2.1.2. Whey protein digestion 10

3.2.2. Structural protection and potential "chaperone" effect **Error! Bookmark not defined.**

3.3 Bioavailability and Insulin-mimetic pathways 11

3.3.1. Intestinal absoprtion .... **Error! Bookmark not defined.**

3.3.2. Cellular action .... **Error! Bookmark not defined.**

3.3.3. Comparative analysis: Camel milk vs Bovine milk**Error! Bookmark not defined.**

3.3.4. Experimental findings .... **Error! Bookmark not defined.**

4. Discussion **15**

4.1 Interpretations of findings 15

4.2 Structural Current challenges and Limitations 17

4.3 Food science perspective 17

4.4 Research gaps 18

5. Conclusion **19**

References .... Error! Bookmark not defined.

1. Introduction

Camel milk serves as an important nutritional source in areas with limited food resources. Especially in arid or semi-arid areas like Asia and Northeast Africa. Camels are well adapted to these environments, making camel milk a key source of nutrition in these areas. The milk is rich in essential minerals, including vitamin A, B, C and E (Khaliq et al. 2024). It also contains important minerals such as zinc, iron, magnesium, sodium, copper and phosphorus. Additionally, camel milk contains a variety of bioactive proteins. Camel milk is distinguished by its relatively low levels of cholesterol and sugar in comparison to other types of milk. Furthermore, it naturally contains insulin-like components (Khaliq et al. 2024). Due to its composition, camel milk is regarded as a functional food with both nutritional and potentially health-related benefits. It is also used in various food products such as fermented dairy products (yogurt and cheese), ice cream, and milk powders (Khaliq et al. 2024).

Diabetes mellitus is a major global health issue. In 2024, it has been reported that approximately 589 million adults are affected worldwide. Among individuals aged 20-79 years that number could reach 853 by the year 2050 (Faustini et al. 2025). Oral administration of insulin is generally challenging. This is because insulin is unstable in the gastrointestinal tract and is exposed to enzymatic degradation during digestion. The proteins are broken down by enzymes which disrupt their secondary, tertiary and quaternary structures. This results in intestinal absorption being limited. However, camel milk shows properties that help protect proteins during digestion. Camel milk is more stable in comparison to other milk as it does not coagulate in acidic conditions. This capacity reduces structural damage to the proteins (Faustini et al. 2025).

The hypothesis of this review is that camel milk proteins are structurally more resilient than bovine milk proteins. They are therefore more likely to survive under gastrointestinal conditions, including gastric acidity and proteolytic digestion (Malik et al. 2012). This makes them potential insulin mimetics candidates.

The objective of this study is to examine the structural stability of camel milk proteins in comparison to bovine milk proteins. The analysis will focus on how those proteins survive in the stomach and their potential function as insulin mimetics.

2. Method

A systematic literature search was performed using the databases Scopus and PubMed following the guidelines presented in PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis). The aim is to ensure transparency and structured reporting of review articles. The search strategy depended on three main concepts: camel milk, antidiabetic components, and gastric stability or digestion. In Scopus the following keywords combinations was used: "camel milk" OR "dromedary milk" AND "insulin" or "insulin-mimetic" OR "antidiabetic" OR "lactoferrin" AND "gastric stability" OR "digest" OR "proteolysis". Similar search was executed in PubMed using both MeSH terms and free-text terms to find relevant articles on camel milk, insulin-mimetic activity and protein digestion processes.

After the initial search, all studies were screened based on their titles and abstracts to assess how relevant they were to the aim of the study. Studies that investigated camel milk or its proteins components in relation to gastric stability, digestion or antidiabetic properties were included. Experimental studies including in vitro and in vivo models as well as review articles were also included. Only articles that was written in English with full text available was considered. Studies that did not focus on camel milk and were not relevant to digestion or insulin were excluded.

After screening all duplicates were removed and the remaining articles were evaluated in full text. A total of 21 articles met the criteria. They were then categories into different themes: gastric stability and enzymatic hydrolysis of camel milk, structural and functional properties of camel milk and last bioavailability and mechanism for potential antidiabetic effects of came milk proteins. During the writing stage 10 more articles were added.

3. Results

3.1. Structural composition of camel milk proteins

Camel milk is a biologically active fluid that is produced in the mammary glands and serves as the primally source of nutrition during the early stages of life. It contains various components including proteins, fast, mineral, lactose and bioactive molecules. These components are not only for nutrition but have physiological and protective functions. Among these various components, protein stands out as the most important due to their structural variety and biological properties (Charles et al. 2025)

Milk proteins are divided into two main groups: caseins and whey proteins. Caseins are insoluble proteins and exist in complex structures called micelles. In contrast, whey protein is soluble and remains dissolved in the aqueous phase of milk. The balance between these proteins may vary between species, influencing the nutritional and physical characteristics of milk. However, in general casein proteins are the main protein while whey proteins represent the minority (Charles et al. 2025).

3.1.1 Casein vs Whey: Unique ratio and lack of β-lactoglobulin

In camel milk, casein is found at approximately 52-87% of the total protein content. While the whey protein content accounts for 20-25% (Charles et al. 2025). In cow milk the casein content is between 80-82% and why protein is around 20%. In comparison to cow milk caseins account for the majority of the protein content. However, the ratio varies more and less, especially in casein content (Abd El-Aziz et al. 2022).

Camel milk casein is composed of four fractions: αs1-casein, αs2-casein, β-casein and k-casein. The proportions of that protein found in camel milk are very different in comparison to cow milk. One of the largest differences is the proportion of β-casein. In makes up approximately 65% of the casein content in camel milk, compared to only 34% in cow milk (Abd El-Aziz et al. 2022). The higher content of β-casein not only influences the structural organization of the micelles but also affects the digestibility of camel milk proteins (Pastuszka et al. 2016). At the same time, camel milk has a lower proportion of αs1-casein approximately 22% compared to 45% in cow milk (Abd El-Aziz et al. 2022). The lower amount of αs1-casein is very important as αs1-casein have been strongly associated with milk allergies in humans (Pastuszka et al. 2016). The lower amount of αs1-casein and higher amount of β -casein in camel milk leads to softer coagulum during digestion in comparison to cow milk (Abd El-Aziz et al. 2022).

A defining characteristic of camel milk is the near-absence of β-lactoglobulin, the dominant whey protein in cow milk and a known allergen. Instead of α-lactalbumin serves as the primary whey protein found in camel milk (Pastuszka et al. 2016). The protein α-lactalbumin of camel milk has an essential role in lactose synthesis and it consists of approximately 123 amino acid residues (Abd El-Aziz et al. 2022). The similarity in the structural to human milk proteins contributes to higher tolerance and digestibility compared to cow milk. The different casein composition and the absence of β-lactoglobulin makes the camel milk structurally unique (Pastuszka et al. 2016).

3.1.2. Insulin and Insulin-like proteins

Camel milk has a high concentration of insulin and insulin-like proteins in comparison to bovine milk (Faustini et al. 2025). The concentration of insulin found in camel milk is approximately 52 U/L which is four times the amount found in cow milk. Camel milk contains several bioactive proteins that are structurally similar to insulin (Charles et al. 2025). The amount of insulin-like proteins found in camel milk are three times higher than in bovine milk. These proteins are able to bind to and activate insulin receptors. They may also be protected from gastric degradation, improving their absorption (Faustini et al. 2025). Camel milk is composed of 51 amino acids that are arranged in two polypeptide chains. The chains are linked tighter but are highly conserved between different mammalian species. Camel insulin is slightly different from other animal insulin by a few amino acids in the sequences (Malik et al. 2012).

3.1.3. Protective molecules: Lactoferrin and immunoglobulins

Camel milk has a high concentration of protective proteins, including lactoferrin, immunoglobins and lysozyme. These proteins exhibit antimicrobial and anti-tumor properties (Abd El-Aziz et al. 2022). Lactoferrin is a whey protein with a structure that allows it to bind iron. Compared to cow milk, camel milk has a higher concentration pf lactoferrin. Another protective protein present in camel milk is immunoglobulins. They are reported to be compatible with human immunoglobulin, further distinguishing them from other types of milk (Pastuszka et al. 2016). Lysozyme is also found to be present with higher concentration in camel milk. It especially exhibits antibacterial activity towards gram-positive bacteria. Lactoperoxidase is resistant to both acidic conditions and proteolytic digestion. In addition, it is described as part of the non-immune host defense system and is associated with bactericidal and growth-related activity (Abd El-Aziz et al. 2022).

3.2. Gastric Stability

3.2.1. Proteolytic Resistance

Camel milk proteins digest differently than other milks in the stomach and the intestines. Studies using a stimulated infant digestion model show that milk types behave very differently, especially during the gastric phase (Miltenburg et al. 2012). In infants, the stomachs pH level is much higher than in adults. While adult gastric pH is usually below 2.0, and infant’s pH rises significantly from 3.2-3.5 to 6.0-6.5 right after feeding. This level typically stays between 4.0 and 5.o for about two hours. Higher pH levels are not ideal for pepsin, a digestive enzyme that works best in highly acidic environments. As a result, infants break down proteins more slowly than adults (Xiao et al. 2023).

Camel milk proteins show unique digestion behavior. While the milk is physically stable, its proteins are biologically fragile once they reach the stomach. A study using a simulated infant digestion model showed that camel milk only retains a small number of intact proteins during the gastric phase. In fact, up to 99.76% of caseins are degraded after just 30 minutes of digestion (Xiao et al. 2023). This indicates that camel milk proteins have less rigid structure and are more susceptible to enzymatic breakdown compared to other milks.

3.2.1.1. Casein digestion

An enzymatic hydrolysis study further demonstrates that camel milk casein is efficiently broken down into smaller peptides. The degree of hydrolysis increased from 3 hours to 6 hours, indicating continuous protein degradation during enzymatic treatment. The study was conducted by isolating casein proteins, followed by enzymatic digestions using specific proteolytic enzymes, and then applying hydrolysis conditions (Mudgil et al. 2021). The protein analysis method SDS-PAGE showed the degradation of intact casein bands, while RP-UPLC analysis confirmed that the main casein proteins were converted into smaller peptides (Mudgil et al. 2021).

The level of hydrolysis was influenced by the type of enzyme used. In breaking down bovine casein, Pronase E was more effective than Alcalase. However, hydrolysis increased with longer incubation time. Overall camel milk casein is described as more resistant to hydrolysis than bovine casein in controlled enzymes experiments. After stimulated gastrointestinal digestion (SGID), protein breakdown results in numerous peptides. Between 36 and 52 different peptide sequences were observed. Many of these peptides contain hydrophobic amino acids, which contribute to their biological activity. Among them peptides such as phenylalanine-leucine (FL), phenylalanine-proline (FP), leucine-methionine (LM) and leucine-proline (LP) were found and are known in literature as bioactive sequences (Mudgil et al. 2021).

These enzymatic breakdown processes lead to positive functional outcomes. Enzymatic inhibition tests were performed against α-amylase, α-glucosidase and DPP-IV. The peptides showed inhibitory effect against them. Camel milk protein hydrolysates showed stronger inhibitory effects than bovine milk protein. The inhibitory activity increased after the gastrointestinal digestions indicating that it plays an important role in activating these functional properties. This study suggests that hydrolyzed camel milk followed by SGID produces peptides with anti-diabetic potential due to their ability to inhibit a-amylase, a-glucosidase and DPP-IV (Mudgil et al. 2021).

3.2.1.2. Whey protein digestion

Camel whey protein also shows strong susceptibility against enzymatic digestion. Although their behaviors differ due to their structural differences. A key factor is due to lack of β-lactoglobulin in camel milk. The protein is relatively resistant to gastric digestion and is found to be more abundant in bovine milk. In a digestion experiment both whey proteins were exposed to a two-step stimulated gastrointestinal system. First the proteins were treated with pepsin under acidic conditions followed by trypsin and chymotrypsin under neutral/alkaline condition. To monitor the degree of hydrolysis free amino group α-NH2 that was released during the process were measured. The method allows us to monitor the extent of the protein that is broken down during digestion (Abderrahmane et al. 2015).

The results showed that camel milk was more sensitive to pepsin digestion, resulting in a higher degree of hydrolysis. In addition, the peptide chain length analysis showed that camel milk peptides were shorter, showing a clear more complete hydrolysis of the original protein structure. Electrophoresis analysis confirmed these findings. The SDS-PAGE showed the disappearance of intact whey protein bands and the appearance of low-molecular weight peptides (Abderrahmane et al. 2015).

3.2.2. Structural protection and potential "chaperone" effect

In the stomach, camel milk does not form stable coagulum like bovine milk. Instead, small casein particles are formed, and they are rapidly emptied from the stomach. These results in faster gastric emptying and shorter retention time. At the end of digestion, no intact proteins remain. The lack of coagulum could possibly allow natural insulin to be unaffected and pass through the gastrointestinal system. Camel milk also contains small fat globules that do not cluster together due to the absence of agglutinin. This improves fat digestion. Camel milk contains higher amounts of protective proteins and has a lower fat content in comparison to bovine milk. All of these contribute to more efficient digestion (Ali et al. 2024).

The stability of specific bioactive proteins during digestion is a major limitation. Lactoferrin is an example, in its free form, it is easily degraded during gastrointestinal digestion leading to a loss of bioactivity. Nano-encapsulation where starch-based nano particles are used is a possible solution. This gives the lactoferrin a protective matrix. The starch nanoparticles act as a "chaperone-like" carriers for lactoferrin during digestion, reducing the accessibility for enzymes in both the gastric and the intestinal phases. As a result, encapsulated lactoferrin maintains its structural integrity. It also retains its inhibitory activity towards α-amylase, α-glucosidase and DPP-IV. Overall, nanocomplexes that act like a protective carrier preserve the proteins functional activity (Mudgil et al. 2025).

Studies have hypothesized that the protentional therapeutic benefits of camel milk lies in the milks unique structure. Camel milk does not easily coagulate at low pH, have different casein composition and larger micelle size compared to bovine milk. Based on these properties it is suggested that insulin may be encapsulated within the micelles structure, passing through the stomach to the intestine. However, the study concludes that there is no direct evidence to prove protein encapsulation (Malik et al. 2012).

3.3. Bioavailability and Insulin-mimetic pathways

3.3.1. Intestinal absorption

Digestion of camel milk proteins in the gastrointestinal tract mainly results in extensive hydrolysis. Most intact proteins are broken down into smaller peptides and free amino acids (Ojha et al. 2025). Very few peptide fragments above 1 kDa were detected after digestion, indicating that most proteins are extensively degraded during the digestive process (Ojha et al. 2025). This suggests that camel milk proteins rarely remain in their original intact form once they reach the intestinal form (Mudgil et al. 2023). During the intestinal digestion all major milk proteins such as casein, whey proteins, lactoferrin and immunoglobulins are extensivly degraded. Only weak or no visible intact bands are observed after enzymatic treatment (xiao et al. 2023).

The smaller peptides may be absorbed though the intestinal wall and are then transported into the circulation to contribute to the biological activity. After absorption, they are distributed to different tissues through the bloodstream (Anwar et al. 2022). However, there is controversy surrounding the extent of the peptide's absorption by the intestinal epithelia to act out the effects they could have (Mohamed et al. 2025). Peptides with a molecular weight below 1 kDa ae considered more likely to be absorbed due to their higher permeability. Their smaller size makes it easier to pass through peptide transporters like PEPT1 and paracellular pathways, increasing their chances of entering the bloodstream (Ojha et al. 2025).

For certain bioactive proteins such as insulin, an *in vitro* experiment shows that they are degraded during the gastrointestinal digestion. Insulin also loses its biological activity before reaching the intestinal absorption phase (Abou-Soliman et al. 2020). Intact insulin is unlikely to be absorbed into the bloodstream under normal digestive conditions (Abou-Soliman et al. 2020).

Nevertheless, some studies suggest that protective mechanisms such as encapsulation in micelles or nanoparticles may allow some protein or peptides to pass through partially unaffected (Malik et al. 2012). In specific cases it has been reported that some components in camel milk can be shielded during digestion. However, those findings remain theoretical and have yet to be confirmed experimentally (Malik et al. 2012). Lactoferrin has been reported to resist gastric digestion and may remain partially intact long enough to interact with receptors in the small intestine. This is however considered an exception rather than a general outcome (Anwar et al. 2022).

Even though intact protein absorption is considered unlikely, experimental studies show biological effects after camel milk consumption. This supports the idea that bioactivity is mainly driven by peptide fragments rather than intact proteins entering the bloodstream (Khan et al. 2025).

3.3.2. Cellular action

Camel milk proteins are broken down into bioactive peptides that affect glucose regulation. The peptides interact with key enzymes and cellular pathways involved in diabetes. One important mechanism is the inhibition of α-amylase, which breaks down starch into glucose (Mudgil et al. 2023). When the enzyme is inhibited, the release of glucose into the bloodstream slows down. This prevents the rapid increase in blood glucose after meals. Camel milk peptides also inhibit dipeptidyl peptidase IV (DPP-IV) (Mudgil et al. 2023). This enzyme degrades incretin hormones such as GLP-1. However, the inhibition of DPP-IV preserves GLP-IV leading to insulin secretion and improves the glucose uptake in the cells. This shows an indirect insulin related effect rather than direct receptor binding (Mudgil et al. 2023).

At receptor level, camel milk peptides have shown direct interaction with insulin receptor (IR). Peptides may activate IR and increase its signaling activity, leading to improved insulin responses in the cells (Anwar et al. 2022). Experimental studies suggest that camel milk whey protein can activate IR and phosphorylation even in the absence of insulin. This suggests that camel milk whey protein can induce insulin-like signaling independently (Ayoub et al. 2024).

When the receptor is activated, important signaling pathways such as AKT and ERK1/2 are stimulated. These pathways are especially important for the regulation of glucose metabolism and how the cells respond to insulin (Ayoub et al. 2024). Among these, the AKT pathway plays a very important role in controlling the movements of glucose transporter 4 (GLUT4) to the cell membrane. Once GLUT4 is moved into the cell membrane, more glucose can enter the cell from the bloodstream (Anwar et al. 2022).

In addition to this, camel milk hydrolysates have shown to increase glucose uptake in liver cells (HEPG2 cells) (Anwar et al. 2022). Similar findings demonstrate that camel whey proteins and their peptides increase glucose uptake making them exhibit an insulin-like effect at cellular level (Ashraf et al. 2021).

Some peptides can bind directly to the insulin receptor. This helps the receptor stay in its active form. The activation of the receptor can be triggered in the absence of insulin (Ojha et al. 2025). The interaction can be allosteric, meaning that the peptides bind to sites on the receptor other than the primary insulin-binding site. This can increase receptor sensitivity and improve signaling (Ayoub et al. 2024). Camel milk peptides may also enhance insulin activity in the presence of insulin, a process known as positive allosteric modulation. The presence of the peptides makes the insulin more efficient. This suggests that camel milk does not replace insulin but helps strengthen its biological effects (Ashraf et al. 2021).

Some hypotheses suggest that camel milk contains small insulin-like molecules. These molecules mimic insulin interaction with the receptor and may directly activate the receptor or enhance glucose uptake (Malik et al. 2012). Some peptide sequences are found similar to human insulin, supporting the idea of insulin-like activity (Agrawal et al. 2022).

Camel milk proteins may also improve the function of pancreatic β-cell function. Some hydrolysates increase the β-cells growth and insulin secretion. This leads to more insulin being available in the body. This also provides an additional mechanism where camel milk may help control blood glucose (Khan et al. 2025). In addition, camel milk proteins support β-cells regeneration and reduce inflammation through their antioxidant and anti-inflammatory properties. This helps maintain healthy insulin producing cells and improve the overall metabolic function (Ali et al. 2024). Overall, camel milk shows antidiabetic effects through several cellular mechanisms

3.3.3. Comparative analysis: Camel milk vs Bovine milk

When comparing camel milk and bovine milk, studies report that camel milk promotes positive blood glucose outcomes. Bovine milk shows no comparable glucose-lowering effects under similar situations (Ayoub et al. 2024). Other comparative studies show stronger antidiabetic effects in camel milk compared to bovine milk (Mudgil et al. 2024). Research shows that camel milk contains higher concentration of whey proteins with bioactive properties than bovine ones. *In vitro* tests showed that camel milk protein had lower IC50 values compared to bovine whey protein hydrolysates indicating stronger inhibitory activity for camel milk (Ashraf et al. 2021). Enzyme inhibition studies showed that camel milk had higher inhibition activity against carbohydrate-related enzymes (Ayyash et al. 2018). Overall, stronger blood glucose lowering effects is observed in camel milk than bovine milk.

3.3.4. Experimental findings

Both laboratory (*in vitro*) and animal (*in vivo)* studies show that camel milk and its peptides have positive effects on diabetes (Yu et al. 2024). *In vivo* studies have shown that the body weight of the type 1 diabetic rat is considerably decreased compared to healthy rats (Khan et al. 2025). Diabetes can lead to weight loss by increasing the breakdown of protein from muscles and by reducing the availability of glucose for metabolism. In addition, low insulin levels reduce the body's ability to synthesize new proteins. After eight weeks of camel milk treatment, body weight was restored in diabetic rats, showing improved metabolic balance. This effect may be related to the high quality of whey proteins in camel milk which may help restore body weight by supporting muscle growth (Khan et al. 2025).

Further experimental studies show that camel milk-derived peptides can improve blood sugar control. A peptide called LLPK showed that it can block dipeptidyl peptidase IV (DPP-IV) (Yu et al. 2024). In type 2 diabetic mice, LLPK treatment decreased fasting blood glucose levels, improved insulin sensitivity and glucose tolerance, and decreased insulin resistance. The treatment also improved lipid metabolism by decreasing lipid content and reducing the fat accumulation in the liver (Yu et al. 2024). Microscopic analysis of the liver tissue showed less liver swelling and tissue damage. Food intake and body weight were lower in the treated mice (Yu et al. 2024).

Review studies also show that camel milk lowers blood glucose levels and reduces the need for insulin therapy (Bakr et al. 2015). Improved blood sugar levels also decreased a range of diabetes related complications such as high cholesterol, oxidative stress, liver and kidney damage and slow wound healing. I addition, camel milk is reported to improve long-term blood glucose control in people with type 1 diabetes (Bakr et al 2015). Therefore, regular consumption of camel milk may potentially reduce the risk of developing diabetes.

4. Discussion

4.1. Interpretations of findings

The findings presented in this review suggest that camel milk differs significantly from bovine milk both in biological activity and in protein structure. Unlike bovine milk, camel milk contains more β-casein, lower amounts of αs1-casein and little to no β-lactoglobulin. Those characteristics contribute to softer coagulum formation during digestion and may also improve digestibility compared to bovine milk. Besides that, camel milk also contains more insulin and insulin-like proteins, as well as protective proteins such as lactoferrin and immunoglobulin.

The structural properties of camel milk appear to play an important role in its behavior during gastrointestinal digestion. Unlike bovine milk, camel milk does not form dense coagulum structures under acidic gastric conditions. Instead, smaller casein particles are formed that may contribute to faster gastric emptying and an altered protein digestion pattern. Although the camel milk proteins are extensively hydrolyzed during digestion, studies constantly show that this hydrolysis lead to the release of many bioactive peptides with antidiabetic activity. Therefore, the antidiabetic activity of camel milk depends on its bioactive peptides rather than intact proteins surviving digestion.

Another important aspect highlighted in this review is the challenge associated with oral insulin. Insulin is normally degraded in the gastrointestinal tract due to the acidic conditions and proteolytic enzymes. This limits its absorption and its biological activity. Camel milk can be seen as an exception because of its high concentration of insulin and insulin-like proteins. However, the findings in this review do not fully support that theory. An in vitro study demonstrated that camel milk insulin is also degraded and loses its biological activity before reaching the intestinal absorption phase. This suggests that camel milk insulin is not behind its strong antidiabetic activity.

Studies have shown that camel milk-derived peptides have direct and indirect insulin related antidiabetic effects. Indirect effects include that the peptides exhibit strong inhibitory effects against enzymes involved in glucose regulation, such as α-amylase, α-glucosidase and DPP-IV. Those effects contribute to slower glucose release and improved insulin secretion mainly through the preservation of GLP-1 activity. Direct activity means that the peptides interact with IR and activate signaling pathways associated with glucose uptake and insulin response even in the absence of insulin. This demonstrates that camel milk peptides not only have indirect activity but also possess insulin-mimetic activity.

Furthermore, studies have shown positive outcomes for type 1 diabetic rats and type 2 diabetic mice. In type 1 diabetic rats, camel milk treatment was associated with reduced insulin requirements, recovery of body weight and improvements in lipid metabolism. In contrast, type 2 diabetic mice lost weight, had lower blood glucose levels and showed reduced insulin resistance. Reduced fat accumulation in the liver was also observed in type 2 diabetes, which suggests that camel milk influences other metabolic disturbances associated with diabetes.

4.2. Current challenges and limitations

Several challenges limit the use of camel milk in clinical and nutritional settings as a functional food for diabetes management. One important reason is the variability in composition between different camel breeds. Experimental studies show that differences in camel breeds can have an impact on the nutritional content and the bioactive compounds in the milk (Mudgil et al. 2023). Therefore, results obtained from one camel breed do not always apply to others. Another limitation is heat treatment. During processing changes in nutrients may happen and can affect the functional properties of camel milk, including its interactions with gut bacteria (Shao et al. 2018). This means that heat treatment may lower or modify the biological effects of camel milk making it important to consider this factor during industrial processing and storage. In addition, there is still a lack of large-scale clinical studies on the antidiabetic effects of camel milk. Although there are many *in vivo* and *in vitro* studies on the antidiabetic activity of camel milk, evidence based on humans is still very limited (Faustini et al. 2025; Bakr et al. 2015).

4.3. Food science perspective

Camel milk has strong potential for application in smart food systems; however, most applications are currently in either research or development stage (Izadi et al. 2025). As previously mentioned, camel milk proteins and their hydrolysates are enzymatically broken down into peptide fractions that retain their biological activity. In addition to antidiabetic activity, these peptides exhibit antioxidant effects, immune modulation and metabolic regulation allowing them to be used as functional food ingredients. Consequently, smart foods can be developed via protein hydrolysis that generates bioactive compounds. However, because most evidence originates from either *in vitro* or *in vivo* studies it is difficult to determine how functional these compounds will be in human beings.

Specific proteins such as lactoferrin have been successfully isolated and incorporated into nano-encapsulation system based on starch nanoparticles (Mudgil et al. 2025). This approach not only protects the proteins during digestion but also preserves their biological activity, including its antidiabetic effect. This suggests that nano-encapsulation is a highly relevant method for smart food development. Nevertheless, this has only been performed under laboratory conditions, leaving it unclear on how well it will function in real food systems.

Camel milks β-casein can be isolated using methods such as chromatography and cold solubilization reaching purity levels that exceed 90% (Lainaf et al. 2024). Camel milk β-casein have both techno-functional and bioactive properties making it attractive for food applications. From a functional perspective, it shows strong emulsifying and foaming ability which is very important in product formation and texture development in foods such as emulsions, foams and diary-based products. On the other side, it is linked to antioxidant and antifungal effects indicating that it can contribute to both food structure and have health benefits. However, more research is required regarding the digestibility and allergenicity of this protein.

Processing camel milk has received growing attention from both researchers and the dairy industry because of its nutritional value and potential health benefits. Camel milk processing remains challenging because of its unique structure and composition, meaning that standard processing methods do not function the same way as they do with bovine milk (Arain et al. 2024). Consequently, identical methods cannot be applied to fermentation and milk powder production. These structural differences cause camel milk to react differently to heat, enzymes and other processing methods. Therefore, new and advanced methods are needed to process camel milk effectively to overcome the industrial challenges faced with camel milk.

4.4. Research gaps

Despite extensive research on camel milk there are still several scientific gaps that remain. One important uncertainty is the incomplete understanding of the bioavailability of camel milk peptides in humans (Ojha et al. 2025). Although *in vitro* and *in vivo* models show that bioactive peptides are formed during the gastrointestinal digestion, it is still not fully understood to what extent these peptides are absorbed and remain biologically active in humans. This means it is not possible to directly translate laboratory findings into clear outcomes in humans.

Another interesting gap is that there is no true identification of all the specific peptide sequences that are responsible for the antidiabetic activity. Because camel milk generates many different peptides, further studies need to be done to characterize those peptides. Most studies are done on whey proteins so it would be interesting to research what bioactive peptides casein generates as it is the main fraction in milk (Ayoub et al 2024).

Another research gap that has not been widely studied is the standardization between different studies. There is still a lot of variation between studies in terms of experimental designs, digestion models and methods used to isolate and identify bioactive peptides. For example, some studies use infant gastric models while others use adult gastric models. This makes it difficult to compare results and draw conclusions. Not only that, but the differences between camel breeds and processing methods also further reduces the comparability between studies.

5. Conclusion

In conclusion, this review demonstrates that camel milk has a unique protein composition that distinguishes it from bovine milk and influences its digestion and biological activity. The higher proportion of β-casein, lower amounts of αs1-casein and the absence of β-lactoglobulin influences the micelle structure and result in a softer coagulation during gastric digestion. Despite the structural differences, camel milk proteins are degraded under gastrointestinal conditions, resulting in a wide range of bioactive peptides. The findings suggest that the antidiabetic effect of camel milk is not primarily driven by its insulin and insulin-like content. Instead, the antidiabetic effects seem to come from the peptides generated during digestion. These peptides contribute to glucose regulation through different mechanisms. This includes slowing down carbohydrate breakdown by inhibiting enzymes like α-amylase and α-glucosidase. Supporting incretin activity by inhibiting DPP-IV which preserves GLP-1 and enhancing insulin-related signaling by activating insulin receptors, which stimulates pathways like AKT and promotes GLUT4-mediated glucose uptake. Laboratory and animal studies support those mechanisms, but uncertainty remains regarding how well these findings translate to humans. The hypothesis that camel milk proteins are structurally resilient and are able to survive digestion in not supported. However, this review concludes that camel milk peptides can be insulin-mimetic.

6. Reference

1. Abd El-Aziz, M., Kassem, J. M., Aasem, F. M., & Abbas, H. M. (2022). Physicochemical properties and health benefits of camel milk and its applications in dairy products: A review. *Egyptian Journal of chemistry*. 65(5). https://doi.org/10.21608/ejchem.2021.92589.4383

2. Abderrahmane, F., Mezmaze, F., Chekroun, A., Saidi, D., & Kheroua, O. (2015). In vitro digestibility of the dromedary whey proteins: potential uses in infant milk allergies. *International Journal of Pharmacy and Pharmaceutical Sciences*. 7(115).

3. Abou-Soliman, N. H., Awad, S., & Desouky, M. M. (2020). Effect of digestive enzymes on the activity of camel-milk insulin. *International Journal of Dairy Technology*. 73(2). https://doi.org/10.1111/1471-0307.12680

4. Agrawal, R. P., Agrawal, R., Ranga, M. N., & Rizwan, M. (2022). Insulin like protein from camel milk and similarity with human insulin. *Indian Journal of Animal Sciences*. 92(1). https://doi.org/10.56093/ijans.v92i1.120933

5. Akan, E. (2021). An evaluation of the in vitro antioxidant and antidiabetic potentials of camel and donkey milk peptides released from casein and whey proteins. *Journal of food science and technology.* 58(10). https://doi.org/10.1007/s13197-020-04832-5

6. Ali, A. H., Li, S., Liu, S. Q., Gan, R. Y., Li, H. B., Kamal-Eldin, A., & Ayyash, M. (2024). Invited review: Camel milk and gut health—Understanding digestibility and the effect on gut microbiota. *Journal of Dairy Science*, 107(5). https://doi.org/10.3168/jds.2023-23995

7. Anwar, I., Khan, F. B., Maqsood, S., & Ayoub, M. A. (2022). Camel milk targeting insulin receptor—Toward understanding the antidiabetic effects of camel milk. *Frontiers in Nutrition*. 8. https://doi.org/10.3389/fnut.2021.819278

8. Arain, M. A., Salman, H. M., Ali, M., Khaskheli, G. B., Barham, G. S., Marghazani, I. B., & Ahmed, S. (2024). A review on camel milk composition, techno-functional properties and processing constraints. *Food science of animal resources*. *44*(4). https://doi.org/10.5851/kosfa.2023.e18

9. Ashraf, A., Mudgil, P., Palakkott, A., Iratni, R., Gan, C. Y., Maqsood, S., & Ayoub, M. A. (2021). Molecular basis of the anti-diabetic properties of camel milk through profiling of its bioactive peptides on dipeptidyl peptidase IV (DPP-IV) and insulin receptor activity. *Journal of dairy science*. 104(1). https://doi.org/10.3168/jds.2020-18627

10. Ayyash, M., Al-Dhaheri, A. S., Al Mahadin, S., Kizhakkayil, J., & Abushelaibi, A. (2018). In vitro investigation of anticancer, antihypertensive, antidiabetic, and antioxidant activities of camel milk fermented with camel milk probiotic: A comparative study with fermented bovine milk. *Journal of Dairy Science*. 101(2). https://doi.org/10.3168/jds.2017-13400

11. Ayoub, M. A., Yap, P. G., Mudgil, P., Khan, F. B., Anwar, I., Muhammad, K., ... & Maqsood, S. (2024). Invited review: Camel milk–derived bioactive peptides and diabetes—Molecular view and perspectives. *Journal of Dairy Science*. 107(2). https://doi.org/10.3168/jds.2023-23733

12. Bakr Shori, A. (2015). Camel milk as a potential therapy for controlling diabetes and its complications: A review of in vivo studies. *Journal of Food and Drug Analysis*. 23(4). https://doi.org/10.1016/j.jfda.2015.02.007

13. Bereda, G., Uthiraphathy, S. & Ahamad, J (2026). Camel Milk as a Functiona Food: Nutrional Composition, Health-Promoting Benefits, and Safety Considerations. *Food Science & Nutrition*. 14(3), https://doi.org/10.1002/fsn3.71638Digital

14. Charles, N. & Oni, F.O. (2025). Composition of Mammalian Milk and Its Comparative Health Benefits: A Mini Review. *NIPES Journal of Science and Technology Research*. 7(1). https://doi.org/10.37933/nipes/7.4.2025.SI293

15. Faustini, M., et.al. (2025). Camel (Camelus dromedarius L. and Camelus bactrianus L.) Milk Composition and Effects on Human Type 1 and Type 2 Diabetes Mellitus: A Review. *Biology*. 14(9). https://doi.org/10.3390/biology14091162

16. Lajnaf, R., Attia, H., & Ayadi, M. A. (2024). A review of camel β-casein: From purification processes, to bioactivity and techno-functionality. *Food Bioscience*. *62*. https://doi.org/10.1016/j.fbio.2024.105060

17. Izadi, A., Khed,at, L. & Mojtahedi, S. (2019). Nutritional and therapeutic perspectives of camel milk and its protein hydrolysates: A review on versatile biofunctional properties. *Journal of Functional Foods*. 60. https://doi.org/10.1016/j.jff.2019.103441

18. Khan, S.H., Devi, U., Yadav, R., Meena, S., Kapila, R. & Kapila, S. (2025). Anti-diabetic effect of camel milk and protein hydrolysates in rat model. *Molecular Biology Reports*. 53(131). https://doi.org/10.1007/s11033-025-11275-8

19. Khaliq, A., Mishra, A. K., Niroula, A., Baba, W. N., Shaukat, M. N., & Rabbani, A. (2024). An updated comprehensive review of camel milk: Composition, therapeutic properties, and industrial applications. *Food Bioscience*. 62. https://doi.org/10.1016/j.fbio.2024.105531

20. Malik, A., Al-Senaidy, A., Skrzypczak-Jankun, E., & Jankun, J. (2012). A study of the anti-diabetic agents of camel milk. *International journal of molecular medicine*. 30(3). https://doi.org/10.3892/ijmm.2012.1051

21. Miltenburg, J., Bastiaan-Net, S., Hoppenbrouwers, T., Wichers, H., & Hettinga, K. (2024). Gastric clot formation and digestion of milk proteins in static in vitro infant gastric digestion models representing different ages. *Food Chemistry*. 43. https://doi.org/10.1016/j.foodchem.2023.137209

22. Mohamed, I. K., Hua, Y., Kong, X., Li, X., Chen, Y., Zhang, C., & Fall, M. (2025). Bioactive camel milk peptides as regulators of insulin receptor signaling: Experimental and computational perspectives. *Results in Chemistry*. 16. https://doi.org/10.1016/j.rechem.2025.102504

23. Mudgil, P., Al Dhaheri, M. K. O., Alsubousi, M. S. M., Khan, H., Redha, A. A., Yap, P. G., ... & Maqsood, S. (2024). Molecular docking studies on α-amylase inhibitory peptides from milk of different farm animals. *Journal of Dairy Science*. 107(5). https://doi.org/10.3168/jds.2023-24118

24. Mudgil, P., Alameri, M., Devarajan, A., Javed, M., Hassan, H. M., Ali Redha, A., ... & Maqsood, S. (2025). Nano-encapsulation of isolated lactoferrin from camel milk in starch nanoparticles: characterization and retention of antidiabetic activity during in-vitro digestion. *International Journal of Food Science & Technology*. 60(1). https://doi.org/10.1093/ijfood/vvaf064

25. Mudgil, P., Kamal, H., Kilari, B. P., Salim, M. A. S. M., Gan, C. Y., & Maqsood, S. (2021). Simulated gastrointestinal digestion of camel and bovine casein hydrolysates: Identification and characterization of novel anti-diabetic bioactive peptides. *Food chemistry*. 353. https://doi.org/10.1016/j.foodchem.2021.129374

26. Mudgil, P., Redha, A.A., P.Nirmal, N. & Maqsood S. (2023). In vitro antidiabetic and antihypercholesterolemic activities of camel milk protein hydrolysates derived upon simulated gastrointestinal digestion of milk from different camel breeds. *Journal of Diary Science*. 105(5). https://doi.org/10.3168/jds.2022-22701

27. Ojha, P., Xia, T., Liangfu, Z., Qinghai, S., Chen, S., Chitrakar, B., ... & Jianxin, T. (2025). Advancements in in vitro simulated digestion-derived peptides for type 2 diabetes mellitus management: From therapeutic challenges to dietary opportunities. *Food Chemistry: X*. 32. https://doi.org/10.1016/j.fochx.2025.103295

28. Shao, Y., & Wang, Z. (2018). Changes in the nutrients of camels' milk alter the functional features of the intestine microbiota. *Food & function*. 9(12). https://doi.org/10.1039/C8FO00812D

29. Pastuszka, R., Barłowska, J., & Litwińczuk, Z. (2016). Allergenicity of milk of different animal species in relation to human milk. *Postepy Higieny i Medycyny Doswiadczalnej (Online)*. 70.

30. Xiao, T., Zeng, J., Zhao, C., Hou, Y., Wu, T., Deng, Z., & Zheng, L. (2023). Comparative analysis of protein digestion characteristics in human, cow, goat, sheep, mare, and camel milk

under simulated infant condition. *Journal of Agricultural and Food Chemistry*. 71(41). https://doi.org/10.1021/acs.jafc.3c03123

31. Yu, Y., et.al. (2024). Characterization and evaluation of the in vitro and in vivo anti-diabetic activities of camel milk protein hydrolysates derived with different protease digestions. *Journal of functional Foods*. 117. https://doi.org/10.1016/j.jff.2024.106227

Publishing and archiving

Approved students' theses at SLU can be published online. As a student you own the copyright to your work and in such cases, you need to approve the publication. In connection with your approval of publication, SLU will process your personal data (name) to make the work searchable on the internet. You can revoke your consent at any time by contacting the library.

Even if you choose not to publish the work or if you revoke your approval, the thesis will be archived digitally according to archive legislation.

You will find links to SLU's publication agreement and SLU's processing of personal data and your rights on this page:

- https://libanswers.slu.se/en/faq/228318

☒ YES, I, Amina Hussein Jimale, have read and agree to the agreement for publication and the personal data processing that takes place in connection with this

☐ NO, I/we do not give my/our permission to publish the full text of this work. However, the work will be uploaded for archiving and the metadata and summary will be visible and searchable.