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The Significance of Carbohydrates in Canine Nutrition: An Integrated Approach to Nutritional Assessment

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Preface

In the last 7 years, the Norwegian University of Life Sciences (NMBU) has truly become a second home to me. After completing my bachelor's degree in 2020, I undertook the challenge of pursuing my master's degree while simultaneously working full-time. It has undeniably been a demanding and sometimes stressful endeavour. However, also very fulfilling!

I was raised in a household where dogs were more than just pets; they were a passion. My parents were deeply involved in breeding, training, and competing with dogs, and I naturally embraced this lifestyle. Today, I own and actively train three Border Collies for competitions. My love for dogs has been a lifelong pursuit, rooted in the experiences of my upbringing. Nonetheless, my time at the Department of Livestock and Aquaculture Science, IHA, has significantly broadened my understanding of various livestock species and fostered a growing interest in canine nutrition. Consequently, it made me want to immerse myself into knowledge about the role of carbohydrates in dogs. Specifically, investigate the nutritional necessity of dietary carbohydrates, the primary sources in commercial dog food, and the impact of different carbohydrates on varied life phases and exercise requirements of dogs.

I would especially like to thank my advisor, Øystein Ahlstrøm, who has been my invaluable source of information and guidance over the past 7 years. His support and ability to bring calmness to even the most hectic of days have been truly appreciated. Thank you for the discussions and diverse perspectives you have shared with me throughout my academic journey at NMBU!

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Rikke Cecilie Hjorth Bergh

Abstract

The origin of the dog has long been controversial in the literature, sparking numerous debates, particularly surrounding its classification as a carnivore, and the importance of carbohydrates in its diet. Dogs do not have a dietary requirement for carbohydrates, and studies on feeding behaviour have discovered they have a low preference for them.

Glucose serves as a vital energy source, with certain tissues, such as the brain, red blood cells, and central nervous system, relying heavily on it as their primarily energy source. However, dogs possess the ability to synthesize glucose from non-carbohydrate precursors found in fat and protein, and carbohydrates are therefore not considered an essential nutrient.

On the other hand, in the absence of carbohydrates, the body's demand for protein nearly doubles to compensate. To spare the protein utilization, dietary carbohydrates can therefore be a valuable source of energy, particularly during energy-demanding phases like pregnancy, lactation, or high-intensity activities such as sprinting.

Dogs who endure sprinting typically exhibit a higher concentration of fast-twitch muscle fibres and can therefore benefit from carbohydrates in their diet. Conversely, dogs engaged in endurance activities, like sled dogs, may face challenges with carbohydrate-rich diets. Research suggests that high-carbohydrate diets may lead to a stiff gait and muscle fatigue, due to lactate accumulation after glucose oxidation.

In cases were dogs experience conditions like diabetes or obesity, the incorporation of fibre with a low glycemic index can rather be beneficial. Fibre will not be digested and absorbed in the same way as simple carbohydrates, but will be beneficial for the dog's intestinal health, to reduce energy and contribute to bulk and a feeling of satiety.

Commercial dog food commonly includes a significant amount of carbohydrates, ranging from 30-60%, though the exact proportion varies widely based on formulation and intended use. Common carbohydrate sources include grains, legumes, vegetables, and berries, with rice proving to be the most digestible source, both in a cooked and raw state. Although carbohydrates are commonly included in commercial dog foods due to their structural importance, raw diets often reduce or eliminate them entirely. While protein sources are typically more costly than carbohydrates, dog food made in Norway using exclusively Norwegian ingredients can still be more cost-effective than imported alternatives with a higher carbohydrate content, thanks to shorter transportation distances and exclusion of custom taxes.

Sammendrag

Hundens opprinnelse har lenge vært diskutert i litteraturen, og debatten går gjerne på hvorvidt hunden skal klassifiseres som en karnivor, og om karbohydrater er essensielt i deres kosthold. Hunder har ikke et ernæringsmessig behov for karbohydrater i dietten, og studier om hundens fôratferd har også vist at de har en lav preferanse for dem.

Glukose er en viktig energikilde, som hjernen, de røde blodcellene og sentralnervesystemet er helt avhengig av som sin primære energikilde. Hunden har derimot evne til å syntetisere glukose fra forløpere som stammer fra fett og protein, og karbohydrater er derfor ikke å regne som et essensielt næringsstoff for hunden.

Derimot vil en tilførsel av næringsstoffet likevel kunne være gunstig, da et fravær av karbohydrater i dietten kan doble kroppens behov for protein. For å spare proteinutnyttelsen, vil derfor karbohydrater være en verdifull energikilde, spesielt under energikrevende faser som drektighet, laktasjon og perioder med høyintensiv aktivitet, som sprint.

Hunder som utøver sprint har vanligvis en høyere konsentrasjon av raske muskelfibre, og kan derfor dra nytte av karbohydrater i kostholdet sitt. Hunder som jobber mer under utholdenhetsarbeid, slik som sledehunder, kan derimot oppleve negative effekter av et karbohydratrikt kosthold. Forskning antyder nemlig at et diet med et høyt innhold av karbohydrater kan føre til stiv gange og muskeltretthet, trolig på grunn av en akkumulering av laktat i musklene etter oksidasjon av glukose. Hunder med diabetes eller fedme kan derimot dra nytte av en diet med lav glykemisk indeks, med inkludering av fiber. Fiber vil ikke bli fordøyd og absorbert på samme måte som enkle karbohydrater, men vil være gunstig for hundens tarmhelse, redusere energiopptaket og bidra til bulk og metthetsfølelse.

Kommersielt hundefôr inneholder gjerne en betydelig andel karbohydrater, fra 30-60%, avhengig av fôrets formulering og bruksområde. Vanlige kilder er gjerne korn, belgfrukter, grønnsaker og bær, hvor ris har vist seg å være den mest fordøyelige, både i kokt og rå tilstand. De fleste fôr inneholder karbohydrater, hovedsakelig på grunn av den strukturelle funksjonen til næringsstoffet, men råfôr har gjerne et redusert innhold, hvor noen også er helt fri for karbohydrater. Generelt er proteinkilder dyrere enn karbohydrater, men et norskprodusert hundefôr laget utelukkende av norske animalske råvarer kan likevel være mer kostnadseffektivt enn importerte hundefôr med høyere karbohydratinnhold, takket være kortere transportavstander og ingen tollavgifter.

Table of contents

1. Introduction

The domestic dog (*Canis lupus familiaris*) is widely recognized as one of the earliest domesticated animals in the world (Wojtaś et al., 2018). The exact timing of the domestication is still a debate among researchers. However, the strongest theory suggests that dogs initially were domesticated from wolves (*Canis lupus*) who were attracted to human settlements as scavengers, feeding on leftover food scraps and waste. Over time, this scavenging behaviour fostered a closer relationship between humans and wolves, gradually evolving them into the domestic dogs we recognize today (Morey, 1994). Extensive research into the behaviour, vocalizations, morphology, and biology of dogs and wolves consistently demonstrates that the grey wolf is the dog's closest wild relative (Galibert et al., 2011; Scott, 1967).

However, the dog's origin has long been controversial in the literature, sparking numerous debates, particularly concerning their classification as carnivores, and the significance of carbohydrates in their diet. Both the wolf and the dog belong to the taxonomic order *Carnivora*, which encompass animals who primarily feed on meat. While dogs are typically categorized as carnivores in conventional animal nutrition (Dyce et al., 1996; McDonald et al., 2011; Vanak and Gompper, 2009), the modern domesticated dog has adapted to eat a more omnivorous diet compared to the wolf. This diet is characterized by a higher proportion of carbohydrates than animal protein and fat. Some argue that dogs do not require carbohydrates in their diet, and a high-protein, low-carbohydrate diet is more appropriate for them. Others believe that carbohydrates are an essential and valuable source of energy, fundamental for the development of a good gut health, and necessary for weight management, particularly in older dogs, through the inclusion of dietary fibre.

Several studies have shown that dogs have adapted unique traits that differentiate them from obligate carnivores. For instance, they have a capacity to convert β-carotene into vitamin A, tryptophan into niacin, cysteine into taurine, and linoleic acid into arachidonic acid— which are specific traits not commonly found in obligate carnivores. Moreover, dogs also seem to have a lower protein requirement compared to obligate carnivore, such as cats (*Felis catus*) (Legrand-Defretin, 1994). Therefore, dogs are more commonly considered an omnivorous species today (Case et al., 2011a), especially by the commercial pet food industry and veterinarians. However, the prevailing view of most researchers is still that dogs are categorized as carnivores, with a greater tendency towards being a facultative carnivore (He et al., 2024; Li and Wu, 2023).

1.2 Method

This thesis is based on a literature review, with information collected from articles found on Google Scholar, PubMed, and books, such as *Canine and Feline Nutrition - A Resource for Companion Animal Professionals* written by Case et al. and *Animal Nutrition* written by McDonald et al.. Information from various dog food companies have also been included, primarily found on their web pages. Frequently used keywords are *canine nutrition, nutritional requirement dogs, carbohydrate sources, gelatinization, digestibility, α-amylase*.

By examining available literature and research, this thesis aims to collectively gather information regarding the significance of carbohydrates in canine nutrition. Specifically, seeking to address the role of carbohydrates during different life stages of dogs. It will highlight the anatomical characteristics of the digestive tract of dogs, which are relevant to understand the significance of carbohydrates in the dog's diet. It will also compare the energy effects of carbohydrates in contrast to fat and protein – and elucidate on how dogs can fulfil their metabolic requirement for glucose, through either dietary sources or alternative metabolic pathways within the body. Additionally, providing an overview of the chemical composition of carbohydrates, the impact of carbohydrates in different life stages and physical activity levels of dogs, the primary sources in commercial dog food, and different inclusion percentages across different dog food formulations.

Examining the importance of carbohydrates in the diets of dogs holds a significant relevance for several reasons. Firstly, it provides a deeper understanding of canine nutrition, and how the nutrient can influence metabolism, digestion, and overall health of the dog. Secondly, when investigating their significance, one may also shed light on potential health implications, and management of health conditions such as obesity, diabetes, and gastrointestinal disorders.

With the emergence of alternative diets, like grain-free and low-carbohydrate formulations, a clarification of any misconceptions about the role of carbohydrates becomes increasingly important, and providing evidence-based insights can empower the pet owners to make informed dietary choices for their dogs.

2. The digestive system of dogs

When exploring the dog's nutritional needs, the digestive system will provide valuable insight into their biological adaptions to different nutrients and dietary components. The following section will outline the key features of the canine digestive tract, with special emphasis on the mouth, stomach, small intestine, and large intestine.

The mouth

The mouth of a dog is the first observable adaption that supports the perception of them being a carnivore (Brady, 2021). Dogs have 42 teeth, with a composition of 12 incisors, 4 canines, 16 premolars and 10 molars. The canines are long and sharp, positioned at the front of the mouth, perfectly designed to grasp, puncture, and kill prey animals. The incisors are small and short, and predominantly used to grip and pull meat from the bones. The premolars are sharp, and can be compared to a knife blade, as their function is to cut the meat into pieces. Lastly, the molars have a somewhat flatter surface, and is used to break down and crush harder material, such as bones and cartilage. The flat surface also makes them ideal to grind and chew plant material (Van Valkenburgh, 1989). However, the mechanical breakdown of foods is often limited, as dogs commonly swallow larger pieces with little to no chewing (Case et al., 2011b). This is further compounded by the fact that dogs lack the ability to move their jaws from side to side. Without this ability, dogs have a reduced capacity to thoroughly grind their food (He et al., 2024), and are less capable of digesting plant material compared to omnivores species. Plant material typically consists of tough cell walls made of cellulose, which require chewing and grinding to help break down and release the nutrients within the plant cells.

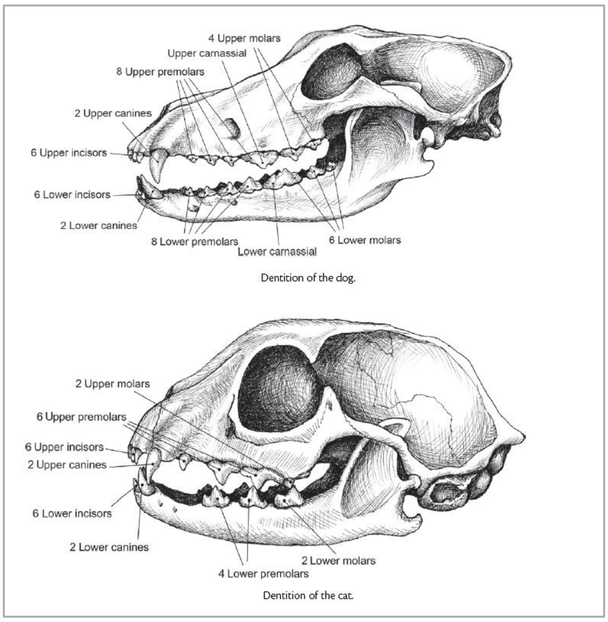


Fig.1. Dog & cats' skull & teeth (Case et al., 2011c)

However, when comparing the oral structure of a dog with a cat, it is evident that dogs exhibit a greater number of teeth, including several molars, compared to cats. This difference suggests that dogs are somewhat better equipped to manage incorporation of plant material, in contrast to the strictly carnivorous dietary requirements of cats (He et al., 2024).

Their mouth also possesses numerous salivary glands that produce saliva to lubricate food, facilitating a smoother swallowing. The canine saliva also contains a high enzymatic activity of lysozyme, which is an enzyme functioning as a defense against pathogenic bacteria and caries (Tenovuo et al., 2000). Carnivores often consume raw meat, which can potentially harbour harmful bacteria. Lysozyme helps neutralize these contaminants by destroying bacterial cell walls, reducing the risk of foodborne illnesses. On the other hand, there is minimal to non-existent presence of the enzyme α-amylase in their saliva (Chauncey et al., 1963; Contreras-Aguilar et al., 2017). α-amylase is responsible for breaking down starch and glycogen into simpler sugars in the mouth. The presence of α-amylase in the mouth of omnivores species provides an early start of carbohydrate digestion and contributes to a more efficient overall digestion of carbohydrates. An important anatomical adaption influenced by a diet typically abundant in starch. However, because dogs from nature are adapted to a diet more restricted in carbohydrates, their digestive system does not heavily depend on starch digestion beginning in the mouth. It will rather occur later in the digestive process, specifically in the small intestine. Interestingly, and perhaps in contrast to this, dogs possess sweet receptors on their taste buds. However, their sensitivity to sweetness is lower than for humans (Li et al., 2006). It's possible that dogs have developed a preference for sweet taste based on the consumption of plant material found in the stomach of their preys.

The stomach

The dog's stomach is relatively large compared to its body size, and compared to omnivorous species, such as humans and pigs (He et al., 2024). The ability of the stomach to hold significant amounts of food in storage is beneficial for carnivorous predators, especially when food availability is not constant. Additionally, the gastric pH is very acidic, ideal for digestion of meat and bones, breakdown of proteins and elimination of pathogenic bacteria (Martinsen et al., 2005). The gastric pH is a controversial topic in the literature, but dogs tend to have a more acidic environment, between 1 and 2, compared to omnivores species (Sagawa, 2009). The stomach also retains ingested meals for a longer period of time, but once emptied into the digestive tract, the transit time is significantly faster (Meyer et al., 1981, 1979). The food's transit time through the entire gastrointestinal tract is half the time compared to pigs (Table 1.).

The small intestine

The majority of nutrient breakdown and absorption takes place within the small intestine. The dog's small intestine is relatively short, and thereby adapted to a diet rich in fat and protein (Sjaastad et al., 2010). However, even if dogs lack amylase in their saliva, they produce pancreatic α-amylase. A famously known study, published in the journal of *Nature* in 2013, found that dogs have evolved genetic changes that enable them to digest starch more efficiently. Dogs were found to have multiple copies of the pancreas amylase gene, AMY2B, compared to wolves. In addition, mRNA levels for the intestinal maltase-glucoamylase gene (MGAM) was 12x higher, and maltase-glucoamylase activity was 2x higher in dogs compared to wolves (Axelsson et al., 2013). This implies that dogs have evolved genetic adaptations to enhance their ability to digest a diet containing higher levels of starch.

The large intestine

Their large intestine is also relatively short, and less developed, compared to omnivores species like the pig (Table 1.) The role of the dog's large intestine is primarily absorption of water and electrolytes which is crucial for maintaining proper hydration and electrolyte balance within the body. Furthermore, it harbours several beneficial bacteria. These microbes ferment the undigested complex fibres and resistant starches from the small intestine, yielding metabolites such as short-chain fatty acids (SCFAs), lactate, and microbial proteins. Additionally, the large intestine synthesizes essential vitamins (B vitamins and vitamin K), strengthens the immune system, and acts as a defence against pathogens. However, when compared to herbivore species equipped with cellulose-digesting enzymes that efficiently break down fibre, dogs possess fewer enzymes and have a shorter retention time in the large intestine. Their digestive system is thereby less developed and lacks the specialized adaptations required for complete fermentation of plant material, in contrast to herbivores (He et al., 2024).

When examining the dog's digestive system, it is evident that their anatomical structure has several adaptions to indicate the dog being a carnivore. This contrasts with many omnivorous species, which have a digestive system better suited for a wider range of animal and plant-based ingredients. For instance, humans have lateral jaw movement and flat-surfaced molars, ideal for grinding and chewing plant materials. Humans also produce α-amylase in saliva to effectively digest starch-rich foods. Omnivorous species typically have longer and more complex digestive tracts, aiding in the efficient digestion and absorption of nutrients from plant-based sources (Table 1) (Mills, 1996).

Table 1 shows the anatomical and physiological differences in the digestive systems of dogs, cats, and pigs. The main characteristic is that the weight of the gastrointestinal tract (GIT) as a percentage of body weight is higher in both small and large breed dogs compared to both neonatal and adult pigs. This is likely because the overall larger size and weight of pigs make the relative size of their GIT per unit of body weight smaller.

In a fasted state, the pH of the stomach fluid appears to be relatively similar between species, when the pH is 2. However, due to the logarithmic nature of the pH scale, a pH of 2.05 in dogs indicates that the hydrogen ion concentration is approximately 8.91 times higher than at a pH of 3 in pigs. Similarly, in a fed state, a pH of 1.08 in dogs indicates that the hydrogen ion concentration is approximately 8.32 times higher than at a pH of 2. Essentially providing a more acidic environment in the stomach acid of dogs.

The small intestine makes up a smaller percentage of the total GIT in dogs (25 %) compared to pigs (40%) and is also shorter (3,9 m per 0,75 m body length) compared to pigs (19 m per 1 m body length). In similarity, the large intestine is also shorter in dogs (0,5 m per 0,75 m body length) compared to pigs (5 m per 1 m body length). The retention time of food in the entire GIT is 23 hours for dogs and 43 hours for pigs.

Table 1. Characteristics of the digestive tract of dogs, cats, and pigs (He et al., 2024)

Animal	Saliva pH	GIT wt (% of BW)	GIT filling (% of BW)	Stomach fluid pH	Gastric half-EMPT (min)	SI length	LI length	Liver wt (% of BW)	Luminal fluid pH			SI volume (% of GIT)	Retention time of food in whole GIT (h)
									Duo	Jej	Ile		
Dog	7.34–7.8	6–7[b] 3–4[c]	3–4[b] 10[c]	2.05[f] 1.08–1.26[g]	72–240	3.9 m per 0.75 m BL[e]	0.5 m per 0.75 m BL[e]	6.82[d] 2.3–3.9[e]	5.7	6.4	6.6	25	23
Cat	7.5	5–6[d] 2–3[e]	3[e]	2.5	22–25[f] 449[g]	1.7 m per 0.5 m BL[e]	0.4 m per 0.5 m BL[e]	4.07[d] 2.46[e]	6.2	6.7	7.0	15	13
Pig	6.0–7.0	2.9[d] 2.3[e]	10[d] 20[e]	2–3[d] 2[e]	160–240[e]	10 m[d] 19 m[e] per 1 m BL	4 m[d] 5 m[e] per 1 m BL	2.7[d] 1.5[e]	6.1	6.6	6.7	51[d] 40[e]	43

[a]Adapted from Kararli (1995), Meyer et al. (1993), and NRC (2006) for dogs; Brosey et al. (2000) and Latimer (1967) for cats; and Gregory et al. (1990), Laerke and Hedemann MS (2012), Merchant et al. (2011), Patterson et al. (2008), and Widdowson (1985) for pigs
[b]Small breed of dogs
[c]Large breed of dogs
[d]Neonatal
[e]Adult
[f]Fasted state
[g]Fed state
[h]Pigs with a normal birth weight
BL = body length; BW = body weight; Duo = duodenum; EMPT = emptying; GIT = gastrointestinal tract; h = hour; Ile = ileum; Jej = jejunum; m = meter; SI = small intestine; wt = weight

Studies conducted on feeding behaviour and nutrient preferences in dogs demonstrates that, when given an option, dogs do not select carbohydrates to be a significant proportion of their diet (Roberts et al., 2018). A collaborative research carried out between the Waltham Centre for Pet Nutrition, the University of Sydney, and the Institute of Natural Sciences at Massey University revealed that dogs have a preference for a high dietary intake of fat, with a favouritism for a macronutrient profile consisting of approximately 63% of their daily calorie intake from fat, 30% from protein, and 7% from carbohydrates (Hewson-Hughes et al., 2013).

Furthermore, a sequence of field-based trials demonstrated that free-roaming dogs exhibit a clear preference for meat, as evidenced by their selection of anything with a meaty scent, regardless of its nutritional value (Bhadra et al., 2016).

However, numerous studies have also shown that dogs possess metabolic adaptations that enable them to fulfil their nutritional requirements without relying solely on meat. They have the capacity to convert β-carotene into vitamin A, tryptophan into niacin, cysteine into taurine, and linoleic acid into arachidonic acid— which are specific traits not commonly found in obligate carnivores. Moreover, dogs also seem to have a lower protein requirement compared to obligate carnivore, such as cats (Legrand-Defretin, 1994).

The extensive research carried out on dogs' eating habits and digestive physiology aligns with the understanding that dogs are well-suited for a carnivorous diet, but with a flexibility to consume plant material. Thereby fitting the description of a facultative carnivore (He et al., 2024; Li and Wu, 2023). Their requirement and utilization of carbohydrates must therefore be evaluated to understand their nutritional needs.

3. Energy sources – Protein, fat, and carbohydrates

When examining the importance of carbohydrates, it is important to compare them with fats and proteins. These macronutrients serve as the primary sources of energy supporting growth, reproductive functions, maintenance, and requirements during physical activity. After absorption, the macronutrients undergo various chemical reactions to produce ATP (adenosine triphosphate), which serves as the body's primary energy currency. However, the different nutrients will be advantageous for varying energy requirements.

Fat is the most concentrated source of energy, providing the body with over twice as many calories (9 per gram) compared to protein (4 per gram) and carbohydrates (4 per gram). After absorption, fat is broken down into fatty acids and glycerol, which can enter the Krebs cycle to generate ATP directly, or be converted into glucose through a process known as gluconeogenesis, which later generates ATP through cellular respiration (Dashty, 2013). Fat provides a sustained energy release with a steady supply of ATP over a longer period of time (Melzer, 2011). It is therefore the preferred fuel during prolonged endurance activities. It also plays an essential role in absorption of fat-soluble vitamins (A, D, E, K), which is important for maintenance of vision, bone health, and immune functions. Additionally, fat also serves as a source of stored energy, simultaneously functioning as a protection of organs, and as a thermal insulator.

Protein is primarily recognized as a fundamental building block. However, if necessary, certain amino acids called glucogenic amino acids can serve as a source of carbon for glucose production during gluconeogenesis in dogs (Melzer, 2011). Gluconeogenesis predominantly occurs when glucose levels are low, for example during fasting, if the dog is eating a diet low in carbohydrates, or if their glycogen stores are depleted. The utilization of fat and protein as substrates for gluconeogenesis obviates the necessity for dietary carbohydrates, however, while gluconeogenesis is essential for maintaining a steady glucose supply, it is generally slower and less energetically efficient.

Carbohydrates are the most important source of glucose, which serves as an important energy source for many tissues. Various tissues have different energy preferences, with the brain, red blood cells and central nerve system relying heavily on glucose as its primary energy source. Muscle tissue, on the other hand, can utilize both glucose and fatty acids and are therefore more flexible.

When comparing energy content in dog food, the value of metabolizable energy (ME) is commonly applied. ME is the amount of energy available for the tissues of the dog's body after subtracting the losses in feces, urine, and gases, from the gross energy content of the food. Because the production of gas is minimal in dogs, only losses in urine and feces are considered (Castrillo et al., 2009).

Likewise, when expressing a dog's energy needs, it is typically done in terms of calories of ME. Scientific reports often include the distribution of metabolizable energy from protein, fat, and carbohydrates, which is valuable for evaluating foods with varying degrees of digestibility or dry matter content. Typically, a fixed digestibility factor is applied for protein, fat, and carbohydrates with 80%, 90%, and 85%, respectively (NRC, 2006). However, these factors can both overestimate and underestimate the ME values of the food, offering only an approximate estimate of energy provision. Recognizing this is essential when evaluating and assessing different effects of dietary carbohydrate levels and sources in dog food (Ahlstrøm, 2024).

4. The dogs nutritional need for carbohydrates

From a nutritional standpoint, dogs do not have an essential dietary need for carbohydrates (Romsos et al., 1976). While they require glucose for metabolism, they possess the capability to synthesize glucose from non-carbohydrate precursors through gluconeogenesis.

The National Research Council (NRC), The European Pet Food Industry Federation (FEDIAF), and the Association of American Feed Control Officials (AAFCO) are the three organizations that establish nutritional guidelines for dogs. None of the nutritional guidelines from FEDIAF, AAFCO, or NRC prescribe a minimum requirement of carbohydrates for dogs. However, it has been debated whether they need an exogenous source of carbohydrates during metabolically stressful periods, such as gestation, lactation, and physically demanding exercises, where the body might not be able to produce adequate levels of glucose themselves.

In Norway and Europe, pet food manufacturers follow FEDIAF's guidelines, which stipulate that protein requirements are influenced by the levels of carbohydrates in the diet. If the carbohydrate level are low or absent, the protein requirement will increase, possibly doubling the minimum requirement of 21 g per 100g DM based on maintenance energy requirements of 95 kcal/kg^{0,75} (FEDIAF, 2019). These requirements are based on a summary of studies carried out by Romsos et al. (1981), Kienzle et al. (1985) and Kienzle et al. (1989), further elaborated upon in Chapter 7.

5. Carbohydrates – Definition, classification, and examples

Carbohydrates can be formed through various biological processes, but primarily through photosynthesis in plants, algae, and some bacteria. Plants will utilize sunlight, carbon dioxide (CO_2), and water (H_2O) to produce glucose and oxygen (Archer and Barber, 2004). Glucose can either be used as an immediate source of energy, stored as spare energy (starch), or incorporated as a structural component (fibre) in the plants.

Carbohydrates are classified into two primary groups: *simple carbohydrates* (sugars), divided into monosaccharides and disaccharides, and *complex carbohydrates*, including digestible starch and non-digestible dietary fibre, further classified into soluble and insoluble fibres (Holesh et al., 2024).

5.1. Simple carbohydrates (sugars)

Monosaccharides

Monosaccharides are the simplest form of carbohydrates and composed of only one sugar unit. They are categorised based on three distinct structural features: the position of their carbonyl group, the number of carbon atoms, and their chiral property (Yahia et al., 2019). Glucose, fructose, and galactose are three important monosaccharides in nutrition, and they all share the same chemical formula $C_6H_{12}O_6$.

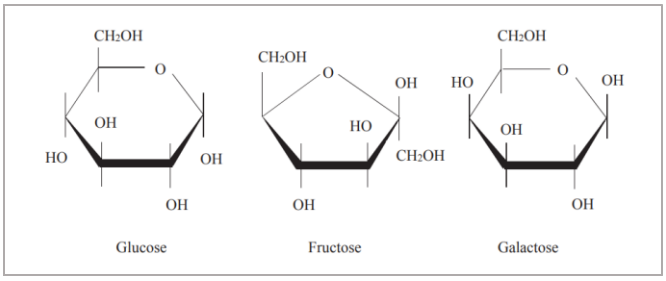


Fig. 3. Structure of glucose, fructose, and galactose (Qi and Tester, 2019)

Glucose, fructose, and galactose

Glucose stands out as the primary monosaccharide, pivotal in cellular metabolism and the maintenance of vital physiological processes in the dog. It is an efficient source of energy and can be rapidly metabolized to produce ATP. Although fructose and galactose possess the same molecular formula as glucose, their distinct structural compositions and atomic arrangements result in differing chemical and physiological characteristics. Neither fructose nor galactose can be directly used as an ATP source and must firstly be converted into intermediates to unlock their potential as an energy source (Deuel, 1936).

Disaccharides

Most available sugars are found as disaccharides in nature. Disaccharides are often called "double sugars" because they are composed of two monosaccharides linked together by a carbon-oxygen-carbon linkage, known as a glycosidic bond. Examples of disaccharides include sucrose, lactose, and maltose. All with the same chemical formula $C_{12}H_{22}O_{11}$.

Sucrose is composed of one glucose molecule and one fructose molecule linked together by a β-1,2-glycosidic bond (Fig.4.). Sucrose occurs naturally in plants, like sugarcane and fruits. The dog's capacity to digest sucrose is influenced by the levels and activity of the enzyme sucrase (β-fructofuranosidase). The activity of sucrase is typically low in young puppies, but increases in adult dogs (Welsh and Walker, 1965).

Lactose is composed of one galactose molecule and one glucose molecule linked together by a β-1,4-glycosidic bond (Fig.4.). Lactose is produced by mammals in their milk, and is vital for nursing babies. Although dogs possess the enzyme lactase (β-galactosidase) required for milk digestion as puppies, its activity diminishes with age. Consequently, feeding adult dogs large amounts of milk or dairy products often result in maldigestion and diarrhoea, due to the osmotic effect of undigested sugar molecules (Buddington et al., 2003; Case et al., 2011d).

Maltose is formed by two glucose molecules with an α-1,4-glycosidic bond (Fig.4.). It is abundant in germinating grains and occurs as an intermediary product during starch digestion. The dog's ability to digest maltose is regulated by the levels and activity of the enzyme maltase (α-glucosidase). Similarly with sucrase, maltase activity is typically also low in puppies but increases in adult dogs (Welsh and Walker, 1965).

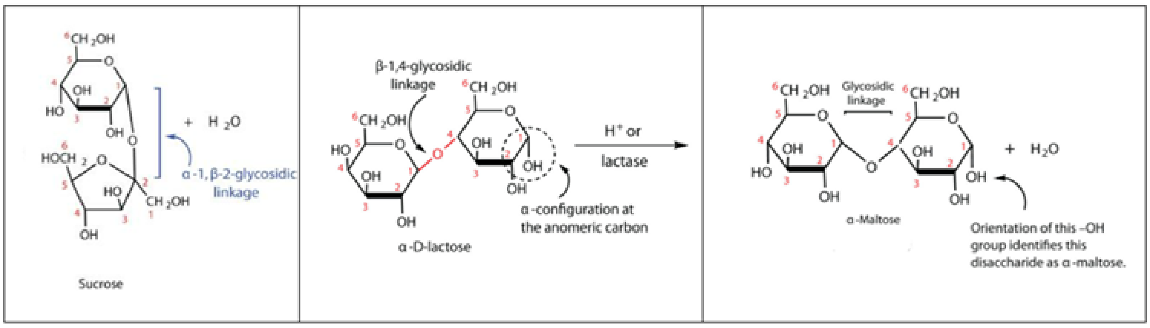


Fig.4. Chemical structure of sucrose, lactose, and maltose (LibreTexts, 2017)

5.2 Complex carbohydrates

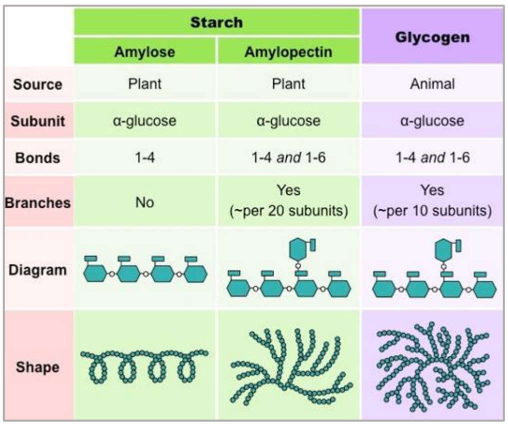
When several monosaccharides are linked together by glycosidic bonds, they form complex carbohydrates. If these chains contain 3-9 sugar units, they are called oligosaccharides. Whereas chains of more than 10 sugar units are called polysaccharides.

Polysaccharides

Starch and glycogen are two well-known digestible polysaccharides, consisting of subunits of glucose arranged in a branched structure.

Starch plays a crucial role as an energy reservoir in plants, and exists in two primary forms: amylose, characterized by an unbranched chain linked by α-1,4-glycosidic bonds, and amylopectin, which is branched with α-1,6-glycosidic bonds occurring approximately on every 20 residues of glucose. In the plant, starch typically exists in the form of granules, and has a distribution of approximately 10-30% amylose and 70-90% amylopectin (Sitrin, 2014).

Glycogen serves as an energy reserve in animals and is predominantly stored in the liver and muscles cells. In the liver, glycogen serves as a reservoir of glucose for the body, helping to regulate blood sugar levels. In the muscles, it provides a readily available source of energy for muscle contractions during physical activity. Additionally, small amounts of glycogen can also be found in other tissues, such as the brain, kidneys and heart (Coxon, 1970). Structurally, it resembles starch with both α-1,4 and α-1,6-glycosidic bonds, but with more highly branched chains. The branching allows for a more compact structure, which increase the storage capacity within the cells. Glycogen is used as a rapid source of glucose in periods of increased energy demand, for example during physical activity, fasting, or stress (Rankovic et al., 2019). However, only a limited amount of carbohydrates can be stored as glycogen, and excess consumption of carbohydrates is rather metabolized to body fat for energy storage.



	Starch		Glycogen
	Amylose	Amylopectin	
Source	Plant	Plant	Animal
Subunit	α-glucose	α-glucose	α-glucose
Bonds	1-4	1-4 *and* 1-6	1-4 *and* 1-6
Branches	No	Yes (~per 20 subunits)	Yes (~per 10 subunits)
Diagram			
Shape			

Fig.5 Comparison of starch and glycogen composition (Ng, 2019).

5.3 Dietary fibre (non-digestible polysaccharides)

Certain polysaccharides, known as dietary fibre, possess a complex structure that hinders their digestion by the enzymes in the small intestine of dogs. Monogastric animals, including dogs, lack significant amounts of enzymes responsible for breaking down the β-linkages in certain fibres. Rather than being broken down and absorbed in the small intestine, they pass into the large intestine relatively intact. Different characteristics distinguish fibres from each other, and they are commonly separated by their solubility, viscosity, and fermentability in the colon (Guillon and Champ, 2000). The two main groups of fibre are known as *soluble fibre* and *insoluble fibre.*

Soluble fibres are hydrophilic and have the capacity to absorb water, resulting in the formation of a gel-like substance. This gel slows down the digestion and prolongs the passage through the small intestine, promoting a feeling of satiation for the dog (Rankovic et al., 2019). In addition, it will slow down the digestion and absorption of nutrients, providing a more stable supply of fuel to the body. Hence, contributing to lower the blood sugar levels. The gel-forming properties will also promote a regular bowel movement and prevent constipation. Because of their water-binding capabilities, soluble fibres may also assist in the managing of diarrhoea (Alves et al., 2021). With higher viscosity compared to insoluble fibres, they are generally more fermentable by the bacteria in the large intestine. The most important byproduct of fibre fermentation is the short-chain fatty acids (SCFA), acetate, propionate, and butyrate. These SCFAs are taken up by the cells in the large intestine, and functions as an energy source for these intestinal cells (Bergman, 1990). Hence functioning as a prebiotic. Moreover, SCFAs encourage the growth of beneficial gut bacteria, such as *Bifidobacterium* and *Lactobacillus,* and inhibit the growth of harmful bacteria, by lowering the pH of the gut environment (Palmqvist et al., 2023). *Bifidobacterium* and *lactobacillus* play a protective role in the gastrointestinal system against potential pathogens (Servin, 2004), as well as synthesising certain B vitamins and vitamin K (LeBlanc et al., 2011). SCFAs also aids in preventing diarrhoea by enhancing sodium absorption (Roediger and Rae, 1982), while butyrate, in particular, possesses anti-inflammatory properties (Shin et al., 2023). However, while some production of SCFAs can contribute to a healthy gut, excessive production can lead to gastrointestinal issues in dogs. Too much fermentation of soluble fibres can result in loose stools, diarrhoea, and excess gas. Additionally also disrupting the normal process of nutrient digestion, leading to nutritional imbalances (Silvio et al., 2000). Examples of soluble fibres include β-glucans, fructooligosaccharides (FOS), and certain types of hemicelluloses.

β-glucans

β-glucans are naturally occurring in the cell walls of bacteria, fungi, yeasts, algae, and plants. They consist of glucose molecules linked together by β-1,3 and β-1,4 glycosidic bonds, with yeast and fungi mainly having β-1,3 bonds and β-1,6 branches. As a soluble fibre, they support a healthy digestion by promoting regular bowel movements and nourishing beneficial gut bacteria. Moreover, β-glucans are also known for their immune-boosting properties, stimulating immune cells, like macrophages, crucial for pathogenic defence (Haladová et al., 2011; Sonck et al., 2010). Research have also suggested that β-glucans may assist in managing allergies and inflammatory conditions in dogs (Beynen, 2019a; Beynen et al., 2011; Jesenak et al., 2014).

Fructooligosaccharides (FOS)

Fructo-oligosaccharides (FOS) are soluble fibres derived from natural fructose polymers, commonly found in various fruits, vegetables, and grains. They are highly fermentable in the hind gut of dogs and are selectively utilized by beneficial bacteria in the gastrointestinal tract. Studies have demonstrated that FOS can increase the population of beneficial Lactobacillus bacteria (Swanson et al., 2002) while simultaneously reducing harmful bacteria such as Clostridium perfringens and Escherichia coli (Beynen, 2019b).

Hemicellulose

Hemicellulose is found in plant cell walls, composed of different sugar units such as glucose, xylose, mannose, galactose, and arabinose. They can be both soluble and insoluble, based on their structure and different linkages. Xylose is a monosaccharide commonly found in hemicelluloses like arabinoxylans. Arabinoxylans bound to cell walls are insoluble, but those not bound are soluble. Psyllium husk is rich in soluble arabinoxylans, and often associated with veterinary diets for intestinal health. However, studies indicate that its branched structure makes it resistant to degradation by gut bacteria of dogs, with only moderate fermentation (Beynen, 2019c).

In contrast, insoluble fibres do not dissolve in water and are generally less fermentable. They remain relatively unchanged as they pass through the digestive system, and predominantly add bulk to the stools. By promoting a regular bowel movement, they reduce the transit time in the digestive tract and ultimately lead to a decrease in nutrient absorption (Wichert et al., 2002) Insoluble fibre have a tendency to bind to other nutrients, such as minerals (e.g., calcium, iron, zinc), and may form complexes that are not absorbed by the body (Chandler, 2016).Examples of insoluble fibres are cellulose, lignin, and certain types of hemicelluloses.

Cellulose

Cellulose is the most prevalent polysaccharide in nature, and the main structural component of plant cell walls. It serves as an insoluble fibre, with glucose molecules connected by β-1,4-glycosidic bonds in an unbranched linear chain. Dogs lack the necessary enzymes capable of hydrolysing the β-glycosidic bonds in cellulose, an are thereby incapable of digesting the polysaccharide. Cellulose is also non fermentable for dogs (Case et al., 2011e).

Lignin

Lignin is not classified as a carbohydrate but is still recognized as a dietary fibre due to its complex organic polymer structure. It plays a crucial role in offering structural support to plant cells and exhibit significant resistance to digestion due to its structural composition of β-configuration and β-bonds between its monosaccharide units. These bonds cannot be broken by the enzymes of the intestinal tract of dogs.

Resistant starch

Resistant starch (RS) is the degradation products from starch, that escapes digestion in the small intestine of dogs. Even though resistant starch is insoluble, certain types are highly fermentable. In similarity with the other fermentable fibres, SCFAs are produced during fermentation, which alters the microbial environment in the colon and strengthens the digestive health and defence of the dog against pathogens.

Generally, it seems that dogs benefit most from sources of moderately fermentable fibres. Research also indicates that a diet containing more than 10% of the dietary dry matter (DM) as fibre can increase the fecal production (Fahey et al., 1990), and the type of fibre affect the fecal quality (Sunvold et al., 1995b, 1995a). High levels of non-fermentable fibre can result in hard, dry feces, potentially leading to constipation. However, an excessive intake of fermentable fibre can cause loose, watery stools or diarrhoea. Moreover, increase the production of gas and provide a frequent bowel movement, which may be inconvenient for dog owners. However, because fibre is less digestible and provides fewer calories it can also help prevent obesity in dogs and be a valuable nutrient to manage diseases, such as diabetes, as discussed in subsequent chapters.

6. Digestion and metabolism of carbohydrates in dogs

The majority of carbohydrate digestion occurs in the small intestine of dogs, as enzymatic digestion in the mouth is constrained by limited production of salivary α-amylase (Pasha et al., 2018). Despite dogs being less adapted to carbohydrate digestion compared to omnivores species, their small intestine possesses enzymes capable of digesting simple sugars and starch.

The process begins with the release of pancreatic saliva containing pancreatic α-amylase (AMY2B) (Rankovic et al., 2019). This enzyme breaks down the α-1,4-glycosidic bonds of amylose and amylopectin, yielding the disaccharides maltose and maltotriose However, it only partially digests amylopectin due to its branched structure, which includes α-1,6 bonds beyond the reach of α-amylase hydrolysis. The degradation of amylopectin will therefore include sections of partially hydrolysed starch, known as dextrin's. Maltose, maltotriose, other disaccharides, and dextrin's will be further broken down and digested at the brush border of the small intestine.

The small intestine features microvilli, which are surface projections of epithelial cells. The microvilli locate enzymes, commonly known as disaccharidases, which are important in the final stages of carbohydrate digestion, breaking down disaccharides into monosaccharides. Lactase hydrolyses lactose into glucose and galactose. Sucrase breaks down sucrose into fructose and glucose. Isomaltase, also known as the debranching enzyme, cleaves the α-1,6 bonds of dextrin's into two glucose molecules. Maltase hydrolyses maltose into two glucose molecules. The monosaccharides glucose, fructose, and galactose are small enough to be directly absorbed into the enterocytes and absorbed into the body.

Not all portions of starch will undergo digestion in the small intestine. Resistant starch, along with fibre and other complex and undigested carbohydrates will reach the colon largely intact and undergo fermentation by the gut microbiota. Bacterial fermentation yields byproducts such as SCFAs, as well as lactic acid and the synthesis of certain B-vitamins and vitamin K. All of which contribute to gut health and provide additional sources of energy. Resistant starch exhibits similar characteristics as dietary fibre regarding its impact on gut health and metabolism.

6.1 Utilization of the monosaccharides

After absorption, glucose, fructose, and galactose are transported to the dog's liver via the hepatic portal vein. Once in the liver, these monosaccharides are either utilized right away for energy usage or stored as glycogen for later requirement by the dog.

Glucose is often required immediately and released directly into the bloodstream to fuel the cellular needs. Fructose and galactose, on the other hand, is required to undergo conversion to produce intermediates that can enter glycolysis or gluconeogenesis, ultimately generating ATP for cellular energy. While fructose is found in fruits and certain vegetables, it is not a primary energy source for dogs, whose main dietary energy from carbohydrates typically comes from grains. Galactose is commonly present in the diet of puppies through their mother's milk but diminishes as dogs transition to solid food.

6.1.1. Utilization and regulation of energy from glucose

The dog's energy needs dictate what happens to dietary glucose. Hormones like insulin and glucagon work together to regulate glucose levels, ensuring blood sugar stability - despite changes in the diet, activity level, or metabolic demands.

If the dogs blood sugar levels rise, for example because of dietary intake of carbohydrates, it stimulates the release of insulin from the pancreas. Insulin will bind to receptors on the surface of cells and facilitate absorption of glucose from the bloodstream. Insulin will thereby reduce the blood sugar levels and promote utilization of glucose by the cells. It also stimulates the activation of enzymes involved in glycogenesis, which converts excess glucose into glycogen in the dog’s liver and muscles for storage and later use. However, only a limited amount of glucose can be stored as glycogen, and excess glucose beyond the dog’s energy requirements are primarily converted into fat during lipogenesis.

Conversely, if blood glucose levels are low, glucagon is released from the pancreas which stimulates the breakdown of stored glycogen into glucose during glycogenolysis. In addition, the release of glucagon also stimulates the synthesis of glucose from non-carbohydrate precursors during gluconeogenesis, such as glucogenic amino acids, glycerol, and lactate. Glycogenolysis involves the breakdown of glycogen stored in the liver and muscle cells of the dog. It occurs primarily as a response to low glucose levels or increased energy requirement when the demand for glucose exceeds the available supply within the body.

6.1.2 Cellular respiration

Once glucose is available and taken up by the cells, it undergoes a series of chemical reactions known as cellular respiration, which dismantle the sugar to produce ATP.

Cellular respiration begins with glycolysis, occurring in the cytoplasm of the cells, where glucose is converted into pyruvate, ATP, and NADH. ATP provides immediate energy for cellular functions, while NADH carries high-energy electrons, and along with pyruvate continues through the cellular respiration process to further synthesise ATP (McDonald et al., n.d.).

Cellular respiration can continue in either an aerobic or anaerobic way. Aerobic respiration occurs in the presence of oxygen and is the most efficient way to yield large amounts of ATP molecules. In situations where the availability of oxygen is limited, for example during intense exercise where the demand for oxygen is higher than the body can supply, the cells can undergo anaerobic respiration instead.

During anaerobic respiration, pyruvate yield from glycolysis is converted into lactic acid (lactate) through a fermentation process, with the oxidation of NADH back to NAD^+, allowing glycolysis to continue producing ATP. Anaerobic respiration is only a temporary solution for energy production, while aerobic respiration is the preferred and more efficient pathway. The reason being that aerobic respiration yields 36 ATP molecules per glucose molecule in total, whereas anaerobic respiration only produces 2 ATP molecules from glycolysis.

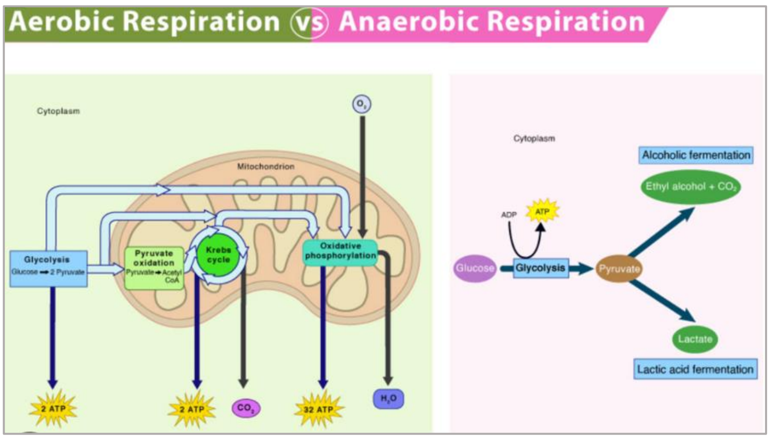


Fig.6. Cellular respiration (Singh, 2023)

6.2 Glycemic index (GI) and health effects

Knowledge about the glycemic index (GI) of various carbohydrate sources are essential to understand how different diets can influence the blood sugar levels of dogs. GI is a measurement of how quickly various carbohydrate-containing foods elevate the blood glucose levels after consumption. The scale ranks from 0 to 100, with pure glucose as a reference point of 100. Foods with a high GI are quickly digested and absorbed, leading to a rapid increase in the blood sugar levels of the dog. Whereas foods with a low GI are metabolized more slowly, causing a gradual rise in blood sugar levels.

For example, a lower glycemic index is known to be beneficial for dogs with diabetes. Dogs predominantly have the form of diabetes that resembles type 1 in humans (Nelson and Reusch, 2014). This condition makes the dogs dependent on insulin to help them regulate their blood sugar levels (Mattheeuws et al., 1984). A consistently high blood sugar can lead to severe health complications, including nerve damage, kidney disease, and eye problems in diabetic dogs (Center, 2018; Good et al., 2003; Morgan et al., 2008). A diet with low GI can therefore contribute to a reduced risk of these complications and long-term health issues. A low GI diet can also benefit obese dogs or older, less active dogs, as many nutrients may have reduced digestibility, resulting in lower calorie intake for these dogs. However, for dogs engaged in physical activities where they need a quick source of energy to sustain heightened energy requirements, a diet with a high GI may be more advantageous. Additionally, underweight, malnourished, or ill dogs experiencing reduced appetite can also find benefit in diets with a high GI to facilitate weight gain.

Rice generally has a higher GI, but it also depends on the type of rice and the processing technique applied (Järvi et al., 1995). Legumes are reported to have a lower GI compared to cereal starches (Jeong et al., 2019). Probably due to their relatively high amylose and antinutritional content. Diets with peas have been reported to have a lower GI than diets with rice and barley (Adolphe, 2013). Carciofi et al. (2008) reported that sorghum and lentil-based diets gave delayed glucose and insulin peaks compared to diets with corn, rice, and cassava (Carciofi et al., 2008a), and Teshima et al. (2021) stated that a diet composed of sorghum and lentils promoted glycemic control in dogs with diabetes (Teshima et al., 2021). Increased fibre intake can aid glycemic control by delaying the digestion and absorption of carbohydrates. Research suggests that diets rich in fibre, particularly insoluble fibre, enhance glycemic management more effectively than low-fibre diets (Kimmel et al., 2000).

6.3 Digestibility of carbohydrates

Numerous factors can influence how dogs digest and absorb carbohydrates. Different types of carbohydrates have varying rates of digestibility, with starches generally having a higher digestibility compared to more complex fibres. However, different sources of starch may also have varying degrees of digestibility depending on the structure and composition of the starch granule, the ratio between amylose and amylopectin, the degree of processing and gelatinization, the particle size, the presence of other nutrients or anti-nutritional factors, and the breed of the dog (Ottoboni et al., 2019).

6.3.1 Digestibility of different carbohydrate sources

Research on different carbohydrate sources indicate that diets containing corn have lower apparent total tract digestibility compared to diets containing rice, and oats have a lower digestibility compared to barley (Walker et al., 1994). Brewer's rice and cassava flour has greater digestibility than corn, sorghum, peas and lentils (Carciofi et al., 2008a), although some studies suggest that rice, sorghum, and corn have similar total tract digestibility (Murray et al., 1999a). Barley and legumes, like peas and lentils, generally exhibit a lower digestibility (Carciofi et al., 2008a; Murray et al., 1999b).

Table 2 shows a comparison of dry matter apparent total tract digestibility and starch ileal digestion of different starch ingredients in extruded diets of dogs. Rice demonstrates the highest overall digestibility with up to 94% dry matter apparent total tract digestibility (DM ATTD) and 99,8% ileal digestibility. Sorghum, corn, and wheat have a somewhat lower digestibility with 94%, 92% and 83,5% DM ATTD, respectively, and 99,7%, 99,5% and 99,8% ileal digestibility. Barley and oats show the lowest digestibility of 84,6% and 70,4% of DM AATD and 99,4% and 98,5% ileal digestibility.

Table. 2 Digestibility of different starch ingredients in extruded diets for dogs (Alvarenga et al., 2021)

Starch Ingredient	Starch Ingredient Inclusion in the Diet (%)	Dog Breed	DM ATTD, %	Starch Ileal Digestion, %
Rice (brewers)	67.0[a], 47.1[b], 59.6[c], 30.0[d], 45.7[e], 77.9[f], 70.5[g], 44.1[h], 52.1[i]	Mongrel dogs[a], Beagle dogs[b,c], Mixed-breed[d,e,g**,i], Spitz dogs[g], Hound bloodline[h]	91.5[a], 79.0[b]*, 89.2[c], 86.6[d], 82.4[e], 90.9[f], 89.4[g], 83.9[h], 94.0[i]	99.5[a], 99.8[h]
Corn (maize)	67.0[a], 53.5[b], 66.7[d], 53.5[e], 31.9[j], 70.5[g], 43.6[h], 34.0[k], 53.5[i], 50.0[l]	Mongrel dogs[a], Beagle dogs[b,j,l], Mixed-breed[d,e,k], Spitz dogs[g], Hound bloodline[f,i]	87.2[a], 82.1[b]*, 84.9[d], 78.6[e], 77.1[j], 83.8[g], 85.4[h], 82.2[k], 92.0[i], 91.9[l]	99.4,[a] 89.9[j], 99.5[h]
Sorghum	53.4[b], 30.0[d], 59.3[e], 70.5[g], 44.2[h], 55.2[i], 64.7[m]	Beagle dogs[b,m], Mixed-breed[d,e,k], Spitz dogs[g], Hound bloodline[h]	79.9[b]*, 86.6[d], 79.0[e], 83.1[g], 79.7[h], 94.0[i], 81.1[m]	99.7[h]
Millet	30.0[d], 70.5[g]	Mixed-breed[d], Spitz dogs[g]	85.2[d], 81.6[g]	n.a.
Wheat	49.1[h]***	Hound bloodline[h]	83.5[h]	99.8[h]
Barley	67.0[a], 51.9[h]	Mongrel dogs[a], Hound bloodline[h]	84.6[a], 82.5[h]	98.8[a], 99.4[h]
Oats	67.0[a]	Mongrel dogs[a]	70.4[a]	98.5[a]
Cassava	42.5[e], 70.0[f], 50.0[l]***	Mixed-breed[e,g]**, Beagle dogs[l]	83.1[e], 91.0[f], 91.2[l]	n.a.
Potato	50.4[h]***	Hound bloodline[h]	83.6[h]	99.6[h]
Lentil	69.5[e]	Mixed-breed[e]	74.5[e]	n.a.
Pea	66.3[e]	Mixed-breed[e]	76.1[e]	n.a.

*values reported from grain medium grinding (451 μm) in this study.
***Starch sources used as flours.
***wet diets on DM basis (%).

6.3.2 Processing conditions

Various processing methods will affect the digestible carbohydrate content in dog food (Beloshapka et al., 2016). Techniques like cooking, grinding, or extrusion can effectively break down starch granules, and render them more accessible to digestive enzymes. Milling of grains before the different cooking techniques will also affect digestibility.

Milling

Whole grains consist of grain brans, which impede the enzymes' access to starch for digestion. Moreover, whole grains contain lipids that limit starch swelling due to hydrophobicity and formations of amylose-lipid complexes (Holm et al., 1988). Grains that are coarsely milled have smaller surface areas for the digestive enzymes, whereas finer grinding of grains breaks the bran open, subsequently promoting a larger surface area and increasing the availability of starch for the digestive enzymes. Whole wheat typically consists of around 50% starch, whereas wheat flour contains approximately 70%. This variance arises due to the elimination of the fibre-rich bran and the protein-dense germ in the flour. Studies suggest that rice bran and wheat bran can lower the overall digestibility of nutrients (Alvarenga and Aldrich, 2018; Burrows et al., 1982; Wichert et al., 2002).

Extrusion

The primary method of dog food production is extrusion, which involves blending of wet and dry ingredients to form a dough. This dough is cooked under mechanical and thermal pressures, resulting in the familiar kibble shape (Joseph and Hebert, 2020). A certain amount of starch is necessary for a proper expansion of kibbles. Heat during extrusion will influence the breakage of intermolecular hydrogen bonds, allowing more water to absorb into the starch molecules. This will cause starch granules to swell and eventually break, leading to gelatinization (Huang et al., 2022).

Research have indicated that digestion of cooked starch can exceed 95% for the dog (Murray et al., 1999a), although some studies report only minor differences in the digestibility of raw and cooked starch. Tubers and legumes, like potatoes and tapioca, typically require heat to deactivate anti-nutritional factors to improve digestibility, while cereal starches, like rice and corn, seem to be well digested even in their raw state (Moore et al., 1980). Nonetheless, data demonstrates an overall higher digestibility of cooked starch (Murray et al., 1999b), with extrusion offering an apparent total tract digestibility of over 99% (Tjernsbekk et al., 2014).

Antinutritional factors

Antinutritional factors are found in plant materials, and affect digestibility by hindering the absorption of nutrients in the small intestine (Fekadu Gemede, 2014). Some antinutrients create an inflammation in the intestine, while others bind to essential nutrients, such as starch, rendering it inaccessible for absorption (Muzquiz et al., 2012). α-amylase inhibitor is an antinutritional factor which is especially present in wheat, rye, barley, soybeans, and sorghum. It inhibits the enzyme α-amylase from breaking down starch (Saunders, 1975; Schuppan, 2017), and therefore reduce the rate at which starch is digested and absorbed. Leading to impaired nutrient absorption. However, this antinutritional factor actually also demonstrates advantageous qualities, especially for diabetic dogs, regulating blood sugar levels by decreasing glucose absorption (Bhutkar and Bhise, 2012).

Lectins are a type of proteins found in many grains, legumes, and vegetables. They contain one or more carbohydrate-binding sites, which can impede carbohydrate absorption (Freed, 1999; Komath et al., 2006). Additionally, they may also bind to cells which stimulates the immune system and leads to inflammation or allergic reactions. In similarity to α-amylase inhibitors, they may be beneficial for diabetic dogs because of their role in carbohydrate absorption.

Phytic acid is an abundant antinutrient in grains and legumes, which serves as the primary storage form of phosphorus in plants. In dogs, phytic acid will act as an antinutrient by binding to minerals such as calcium, iron, zinc, and magnesium, forming insoluble complexes known as phytates (Akande et al., 2010; Kies et al., 2006). Additionally, they may also inhibit the activity of digestive enzymes, such as α-amylase. While heat treatment typically eliminates antinutritional factors, studies indicates only a minimal effect on phytic acid (Gualberto et al., 1997).

Maillard reactions

During extrusion the heat treatment may also produce Maillard products. Maillard reactions are chemical reactions that produce Maillard products between amino acids and reducing sugars, in the presence of heat (van Rooijen et al., 2014). These reactions form products that are unavailable for utilization by the body (van Rooijen, 2015). Some products can be partially absorbed through the intestinal tract but still be unavailable for cell use (Finot, 2005; Moughan, 2003). Lysine is the most important source of reactive amino groups for the formation of Maillard reactions (Hemmler et al., 2018). This amino acid is crucial for growth, making Maillard reactions particularly unfavourable in terms of nutrition for puppies.

Data also indicates that Maillard reactions can produce toxic compounds called acrylamide (Zhang and Zhang, 2007). This toxin has been recognized as "likely to be carcinogenic" for humans, and high levels have also been shown to cause damage to the nervous system as well as giving reproductive difficulties (Dearfield et al., 1988; Tilson, 1981). Since acrylamide is formed at temperatures above 120 degrees, dry extruded dog food is especially susceptible to acrylamide formation. While data on extruded dry dog food is limited, a study in 2013 found moderate levels of acrylamide compared to human food (Veselá and Šucman, 2013). However, the presence of this carcinogenic compound in pet food remains a concern.

6.3.3 Amylose and amylopectin

The structural differences between amylose and amylopectin influence the digestibility of starch in several ways. Amylose is a linear molecule consisting of glucose units linked together by α-1,4 glycosidic bonds. Whereas amylopectin is a branched molecule with additional α-1,6 glycosidic bonds, resulting in a highly branched structure. The branched structure makes it more accessible to digestive enzymes, and as a result the starches with higher amylopectin content tend to be more easily digested compared to those with higher amylose content. Additionally, amylose molecules are more prone to forming the gel-like structure upon gelatinization. This gel-like structure can slow down the digestion of amylose-rich starches, and create a physical barrier that limits enzymatic access to starch molecules.

6.3.4 Digestive capacity in different dog breeds

Research has also explored how different dog breeds possess varying abilities to digest starch. Ancient breeds such as the Samoyed, Greenland Sledge dogs, and Siberian Huskies exhibit lower levels of AMY2B activity (Arendt et al., 2014; Ollivier et al., 2016), suggesting they may have experienced less pressure to adapt to starch-rich diets compared to other breeds. Conversely, the German Shepherd and Springer Spaniel show higher levels of AMY2B expression, indicating potential adaptation to scavenger diets (Arendt et al., 2014). Further investigations by Arendt et al. (2016) across global dog populations revealed that dogs from agrarian regions tend to have higher gene copy numbers of AMY2B, while those from non-agrarian regions have lower gene copy numbers (Arendt et al., 2016).

7. Requirement during various life stages and activity levels

The physiological need for glucose varies throughout different life stages and activity levels of dogs. Although glucose is vital for all dogs, it becomes especially crucial during phases of growth and development, intense physical activity, pregnancy and lactation, times of stress or illness, and in specific health conditions.

7.1 During gestation and lactation

During gestation and lactation, the need for glucose typically increases. Glucose serves as the main energy source for fetal development, particularly for the growth of the brain and central nervous system, as well as for lactose production in milk. However, the necessity for dietary carbohydrates in pregnant and lactating females seems to be influenced by the protein concentration in their diet.

Romsos et al. (1981) examined the reproductive success in Beagle females fed either a diet with 44% of the metabolizable energy from carbohydrates of corn starch (diet 1) or a diet with 0% of the metabolizable energy from carbohydrates (diet 2). This study concluded that pregnant female dogs require dietary carbohydrates for optimal reproductive functions. Several of the females eating diet 2 experienced hypoglycemia, alongside depressed alanine and lactate levels, and higher levels of free fatty acids and β-hydroxybutyrate, indicating ketosis. Moreover, the litter size was smaller, and the mortality rate was higher, with 63% survival rate compared to 96% survival rate amongst puppies from females fed diet 1. Only 35% of the puppies from females fed diet 2 survived at 3 days old. During lactation, it was also observed that females on diet 2 produced milk with less energy from lactose and a higher percentage of energy from fat compared to females on diet 1. However, puppy growth was unaffected (Romsos et al., 1981).

Fig.7. Lactating female Border Collie with puppies

The conclusions drawn from Romsos et al.'s study were later challenged by Blaza et al. (1989). This study examined the effects of feeding female dogs a carbohydrate-free diet during gestation and lactation (Blaza et al., 1989). Beagle and Labrador females were fed either a carbohydrate-free diet made of meat, poultry, offal, bone grit and soya protein, or a diet containing 3% (by weight) of maize starch. This study found no notable variations between the two dietary groups regarding gestation length or litter size, weight, or viability of puppies.

In contrast to the findings of the aforementioned studies, Kienzle et al. (1985) observed a notable impact of the pregnant female's diet on the birth weight of the puppies. However, this effect was also found to be influenced by the protein content. The study investigated the effects of two carbohydrate-free diets, each with varying protein concentrations, on pregnant and lactating females. Offspring from females fed a carbohydrate-free, low-protein diet (comprising 20% of calories from protein) exhibited a significantly reduced birth weight (60–70% of normal weight) and an increased rate of perinatal loss. Conversely, no differences in litter size or birth weight were observed among females fed a carbohydrate-free but protein-rich diet (comprising 42% of calories from protein) (Kienzle et al., 1985).

Fig.8. Lactating female Shiba Inu with puppies

Ultimately, the differences in outcome between the study conducted by Romsos et al. and Blaza et al. was presumably linked to variations of protein levels in the diets. Romsos et al.'s initial study had 26% protein, while the second set of experiments had 51% and 45% protein (Case et al., 2011f). In the absence of carbohydrates, higher protein levels ensure an adequate supply of gluconeogenic amino acids, facilitating the maintenance of plasma glucose levels through gluconeogenesis, even during the heightened demands of gestation and lactation. Consequently, the hypoglycemia observed in Romsos et al.'s study likely stemmed from a deficiency in gluconeogenic precursors (Case et al., 2011f).

This hypothesis were further supported by Meyer and Kienzle's study from 1989, examining the effects of carbohydrate-free diets containing different levels of protein on reproduction in the bitch (Meyer and Kienzle, 1989). Data from this study affirmed that carbohydrate-free diets fed to pregnant and lactating females can support normal performances, given that the food have sufficient supply of available gluconeogenic precursors. Meyer and Kienzle estimated that female dogs need approximately 7 g of digestible crude protein per unit of metabolic body weight, if carbohydrates are included in the diet. In the absence of carbohydrates, the protein requirement rise to about 12 g. Lactating females seem to require between 13 and 18 g of protein per unit of metabolic weight when consuming a diet with carbohydrates and 30 g when consuming a carbohydrate-free diet.

The data presented in the conducted studies suggest that, even during periods of heightened glucose requirements such as gestation and lactation, pregnant and lactating females may not require dietary carbohydrates; however, they exhibit an elevated need for protein when provided with a carbohydrate-free diet.

7.2 Physically demanding performance work

Generally, all working dogs have a higher requirement for energy compared to the typical maintenance needs of an adult dog. However, the specific nutritional demands can vary depending on the nature of the work and the intensity of the performance. Our understanding of the nutritional needs of working dogs largely stems from research conducted on greyhounds and sled dogs. Sled dogs are recognized for their robust endurance, pulling sleds over extensive distances in demanding, cold environments, thus representing the ultimate canine endurance athlete. In contrast, Greyhounds engage in brief yet intense bursts of high-speed running during racing or lure coursing. Nonetheless, the fundamental aspect of physical activity is to ensure that muscle fibres receive a steady supply of ATP to fuel muscular work. Thus, various energy sources may be suitable for different types of work. Studies investigating the various muscle fibre types in dogs reveal that they possess three main types: Type 1 (slow-twitch), Type 2a, and Type 2b (fast-twitch). Slow-twitch fibres have a high oxidative capacity and prefer fatty acids as a substrate for ATP production. They are characterized by their preference for aerobic metabolism and are crucial for endurance activities. Conversely, fast-twitch fibres have a lower oxidative capacity and prefer glucose, but have the capacity to utilize both aerobic and anaerobic pathways, making them vital for high-speed sprinting events (Armstrong et al., 1982).

Fat serves as the primary energy source for dogs during periods of low energy expenditure (Paul and B Issekutz, 1967; Therriault et al., 1973). Findings indicate that dogs exhibit approximately double the level of fat oxidation during exercise compared to humans (Hill, 1998), and are well adapted to endurance exercise because they exhibit a large amount of muscle fibres with high aerobic capacity (Cave, 2013). Moreover, studies have indicated that elevated carbohydrate levels in the diet can detrimentally affect the performance of endurance dogs. This is believed to occur due to the accumulation of lactic acid in muscle cells, which contributes to muscle fatigue and hinders sustained muscular effort over prolonged periods.

Fig.9. Sled dogs during winter race (vomshop.no, 2024)

In a study conducted in 1973 on 16 sled dogs (Siberian and Alaskan Huskies), both purebred and crossbred with German Shepherds, reducing dietary carbohydrates improved running performance. Initially fed a high-carbohydrate diet, the dogs experienced stiff gait during races. Transitioning to a diet rich in fat and protein resolved lameness, possibly due to reduced lactic acid accumulation. Additionally, coprophagy observed with high-carb diets ceased shortly after dietary changes (Kronfeld, 1973).

Reynolds et al. (1994) demonstrated that providing a high-fat diet to working dogs before and during conditioning training improved the dogs' capacity to utilize and mobilize fatty acids as the primary energy fuel. The study was conducted on 16 Alaskan Huskies divided into two groups, where one group was fed a high-fat diet (group 1), with 60% of the calories from fat, and the other group was fed a high-carbohydrate diet (group 2), with 60% of the calories from carbohydrates. The diets were provided 4 weeks before, and 8 weeks during the conditioning program. Dogs in group 1 exhibited significantly higher pre- and post-exercise free fatty acid concentrations compared to those in group 2, even before undergoing training. Free fatty acid levels in the blood are considered a key determinant of fatty acid utilization by muscles and are accepted as an indicator of fatty acid metabolism. The study concluded that feeding a high fat diet, even before the onset of training, could be beneficial to prepare the dog for work by encouraging a more efficient mobilization and metabolism of fat for aerobic muscle work (Reynolds et al., 1994).

Another study echoed the findings of Reynolds et al., by investigating the impact of a high-fat diet on oxygen consumption (VO_2 max), mitochondrial volume, and maximal rates of fat oxidation in Labrador Retrievers trained for endurance (Case et al., 2011g). Vo_2 max is a measurement of the maximum amount of oxygen that an individual can utilize during intense exercise. An increase of dietary fat from 15% to 60% of the calories led to nearly a 50% rise in VO_2 max and a 45% increase in maximal fat oxidation during aerobic exercise of the Labrador Retrievers. Muscle mitochondrial volume also surged by 50%. These results highlight the improved efficiency of fat utilization and aerobic capacity, along with stimulated mitochondrial growth, with a higher fat content in the diet. Such data also highlights the central role of nutrition in stamina and performance of the dogs, since training alone typically increase Vo_2 max and maximal fat oxidation by only 15-20% (Morgan, 2010).

Research carried out by Reynolds et al. in 1995 also examined the energy metabolism of endurance-trained sled dogs during periods of anaerobic activity (Reynolds et al., 1995). Dogs fed a high-carbohydrate diet exhibited higher muscle glycogen stores compared to those fed a high-fat diet. However, the high-carbohydrate diet also resulted in greater glycogen utilization during anaerobic tests, depleting stores similarly to the high-fat diet. Researchers concluded that feeding a high-fat diet to endurance-trained dogs not only primes the muscles to efficiently utilize free fatty acids as an energy source, but also conserves the glycogen stores for more prolonged usage.

To facilitate an ongoing metabolism of free fatty acids, a certain degree of glycogen metabolism must occur because the oxidation of free fatty acids require oxaloacetate, which is derived from the breakdown of glucose via glycogenolysis. Maintaining a sufficient store of glycogen is therefore also important. The dogs capacity of glycogen storage varies depending on factors such as breed, size, and fitness level, but overall, dogs tend to exhibit similar levels of glycogen storage compared to humans (Hoenig, 2014). However, there are differences in the distribution, where humans primarily store it in the liver, and dogs primarily in muscles (Weibel et al., 1996).

For endurance performance, feeding a diet higher in fat is seen to be more successful to spare glycogen stores, rather than feeding a diet thought to increase glycogen stores. However, Greyhounds, sporting dogs (flyball, agility, frisbee), and hunting dogs are primarily involved in short and high-intensity physical activities, frequently demonstrating a more anaerobic metabolism. Research have also shown that greyhounds have a higher proportion of fast twitch muscle fibres (Guy and Snow, 1981). The primary source of energy for this type of exercise is carbohydrates. Both muscle glycogen and circulating blood glucose supply energy to muscles during anaerobic metabolism (Saltin and Karlsson, 1971).

Fig.10. Border Collie doing agility

Post-race biochemical data collected from racing Greyhounds of different sprint lengths indicate that the sprint-racing dogs rely primarily on anaerobic metabolism for energy (Dobson et al., 1988), as portrayed in a higher lactate level in the blood post-race compared to pre-race (Ilkiw et al., 1989; Nold et al., 1991). Toll et al. (1992) found that Greyhounds demonstrated reduced running speeds as dietary fat increased from 31% to 75% of the metabolizable energy, simultaneously lowering the carbohydrate levels (Toll et al., 1992). whereas Hill et al. (2000) found that Greyhounds ran faster when dietary fat increased from 35% to 32% of the metabolizable energy and dietary protein increased from 21% to 25% (Hill et al., 2000).

Fig.11. Dog race during lure coursing (lurecoursing.no, 2024)

Conversely, Hill et al. (2001) found evidence that feeding a diet high in protein and fat, but low in carbohydrates, may have a negative effect on racing performance. 8 adult Greyhounds were fed either a high-protein (HP) diet comprising 37% of metabolizable energy (ME) from protein, 33% of ME from fat, and 30% of ME from carbohydrate, or a moderate-protein (MP) diet with 24% of ME from protein, 33% of ME from fat, and 43% of ME from carbohydrates over a period of 11 weeks. This study was a crossover study, where the dogs did 11 weeks on each diet. Each week, the dogs ran a distance of 500 meters. When fed the HP diet compared to the MP diet, the racing times of the dogs were 0,18 seconds slower. These observations led to speculations that the reduced performance could be a result of the lower carbohydrate levels, and insufficient use of protein as an energy source (Hill et al., 2001).

Subsequent studies display differing results, yet all suggest that the performance of Greyhounds appears to diminish with reduced carbohydrate levels. Nonetheless, there's a chance that alterations in multiple nutrients during research may have synergistically interacted, amplifying their influence beyond what would be expected if each nutrient were examined individually.

7.3 During energy restriction

Inclusion of carbohydrates and can be strategically utilized during energy restriction, primarily through the inclusion of complex carbohydrates and low fat. Energy restriction can be beneficial for dogs that are overweight, obese, or prone to weight gain. It can also be appropriate for dogs with certain medical conditions such as diabetes.

In a study conducted by Romsos et al. (1976) female Beagle dogs where fed different diets ranging in energy derived from carbohydrates. The protein content remained consistent at approximately 23%. At the end of the study, dogs fed the high carbohydrate diet (62% of the energy from carbohydrates) exhibited lower levels of body fat compared to those on the lower carbohydrate diets (20-42% of the energy from carbohydrates) (Romsos et al., 1976). In another study, dogs were fed diets with varying composition of all macro nutrients. Dogs on a high-fat diet (with 51% energy from fat, 20% energy from protein, and 29% energy from carbohydrates) were found to have increased body weight compared to those on a high-carbohydrate diet (with 23% fat, 18% protein, and 59% carbohydrates), despite no significant difference in energy intake between the two groups (Romsos et al., 1978).

Fig. 12. Obese Labrador Retriever (topdoghealth.com, 2017)

Fibre is the primarily source of carbohydrate which can function as a dietary diluent, reducing the total energy density of the food. With obesity rates rising, particularly in elderly dogs who normally experience a reduction in daily energy needs (Taylor et al., 1995), it is essential to carefully monitor the dogs calorie intake to prevent obesity. Especially, since recent research indicates that the increasing rates of obesity in dogs have led to higher incidences of health issues such as hip dysplasia, osteoarthritis, insulin resistance, and certain neoplasia's (German, 2006). Studies on lean dogs show that they typically consume a higher amount of crude fibre in comparison to overweight dogs (Heuberger and Wakshlag, 2011). Dietary fibre, particularly less fermentable fibres, has been shown to decrease hunger and increase satiety by adding bulk to the stomach and intestines, delaying gastric emptying, and prolonging transit time. However, diets including both high levels of crude fibre and protein has been found to be even more (Weber et al., 2007), and additionally resulting in a greater weight- and fat loss in dogs, compared to a high-protein and medium-fibre diet (German et al., 2010).

Research also shows that dogs who eat a high-fibre and low-fat diet exhibit a faster rate of weight loss compared to those who eat a high-protein and high-fat diet. Despite receiving the same intake of metabolizable energy (Fritsch et al., 2010). While this study did not identify the precise reason for this, researchers hypothesized that since it was conducted in a home setting without monitoring of supplementary energy intake for the dogs, owners of dogs on the high-protein and high-fat diet might have been offering additional food outside the study. This could be due to their perception that the portion size provided was insufficient for their dogs.

Most research suggest that the satiating effect of fibre, coupled with its indigestibility, aids in controlling energy intake in dogs. However, excessive fibre intake can also decrease the nutrient digestion and interfere with absorption of other nutrients like fat, calcium, zinc, and iron (Case et al., 2011h). An increased fibre content in foods formulated for weight loss in dogs has also been shown to reduce the food's protein digestibility. (Weber et al., 2007). If a diet high in indigestible fibre is also low in other essential nutrients, it is possible that the food can cause nutrient deficiencies. If the dog is also fed restricted amounts, for the purpose of a fast weight loss, the risk of nutrient deficiencies is further increased.

7.4 DCM in dogs

Dilated cardiomyopathy (DCM) is a heart condition characterized by the enlargement of the heart chambers and decreased ability to pump blood effectively. DCM is known to have genetic predispositions in certain dog breeds; however, recent concerns have arisen regarding a potential link between grain-free diets and the development of DCM in dogs (Quilliam et al., 2023). The US Food and Drug Administration (FDA) reported the potential link between DCM and diets containing peas, lentils, legumes, sweet potatoes, or potatoes in 2019. One hypothesis is that these ingredients, which are often used as substitutes for grains in grain-free formulations, may impact the absorption of nutrients which are critical for cardiac health, such as taurine. Taurine is essential for normal heart functions, and deficiencies have been implicated in the development of DCM in dogs (Smith et al., 2021). Yet, a study involving healthy dogs of diverse breeds fed a high-pea diet found no deficiencies of taurine, but did observe adverse alterations indicative of early-stage DCM (Cavanaugh et al., 2021). These results suggest that the exact mechanisms by which diet may contribute to the development of DCM are still not fully understood. Additionally, there are many factors that can influence an individual dog's risk of developing DCM, including genetics, environment, and potentially also the diet.

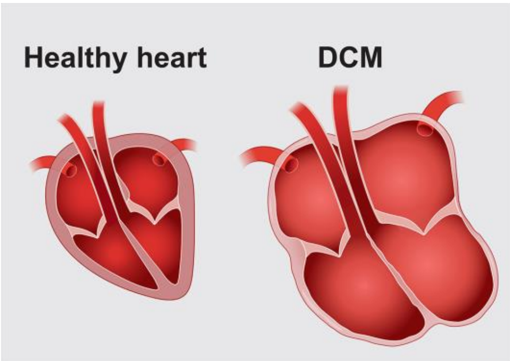


Fig. 13. Presentation of a healthy heart and a hearth with DCM (PDSA, 2024)

8. What are the main sources of carbohydrates in dog food?

Commercial dog food commonly includes a significant amount of carbohydrates, ranging from 30-60%, though the exact proportion varies widely based on formulation and intended use of the food (Daina et al., 2023)

Dog food generally falls into three categories: dry (kibble), wet/canned, and raw. Wet/canned and raw dog foods typically feature lower carbohydrate levels compared to dry kibble, due to higher proportions of protein and fat derived from animal-based ingredients. During the processing of kibble, meat and animal-derived ingredients possess a challenge associated with the extrusion process and the development of high temperatures during the cooking process (Semple, 2020). Meat tends to have high moisture and fat levels, which can hinder friction within the extruder barrel, resulting in suboptimal cooking temperatures and expansion. Therefore, starch plays a crucial role as it acts as a binder, enhancing processing efficiency, while also gelatinizing and expanding under heat and pressure, contributing to the characteristic texture of extruded products. However, this primarily offers a structural advantage for the food rather than a nutritional advantage for the animal. Considering the anatomy, physiology, and nutritional requirements of dogs, one might argue that carbohydrates should not be the predominant macronutrient in their food, despite providing easily accessible energy.

The most common sources of carbohydrate in dog food include different types of grains (wheat, corn, rice, barley, and oats), legumes (peas, lentils, and beans), potatoes, root vegetables (carrots and beets), fruits and berries (apples, bananas, and blueberries). Rice, wheat, corn, barley, oats, potatoes, and peas are commonly utilized as primary sources of starch, oats and rice bran are often incorporated for their soluble fibre content, while wheat bran and cellulose are preferred sources of insoluble fibre. In grain-free diets, carbohydrates are commonly sourced from potatoes, legumes, root vegetables, tapioca, and fruits.

In general diets, grains are commonly included as either meals or grits. Grits are finely ground without the outer coating (bran) of the grains, while meals contain the bran. Consequently, grits tend to have more digestible starch, while meals have slightly higher fibre and protein content.

Manufacturers are not required to list carbohydrates on the label, and it is therefore seldom declared. However, it is required to state the crude fibre content, and some provide the percentage of nitrogen-free extract (NFE), which represents the digestible and soluble carbohydrates of the food.

8.1 Starch sources

Rice stands out as one of the most easily digestible starch sources for dogs, both in a cooked and raw state (Murray et al., 1999b). It was originally utilized as a novel carbohydrate source in diets developed for dogs with hypersensitivity. Because of this, rice has been perceived as a "hypoallergenic" ingredient, although it lacks any inherent hypoallergenic characteristics. Conversely, wheat has garnered a reputation for triggering allergies. With slightly higher protein and gluten content compared to other cereal grains, it is often wheat is often believed to be a source of hypersensitivity in dogs (Case et al., 2011i). Barley and sorghum are starch sources with slower digestion rates than rice and corn, which ultimately contribute to a slower postprandial glucose and insulin response (Carciofi et al., 2008b). Conversely, peas and lentils exhibit lower digestibility, even after extrusion (Bednar et al., 2001), likely due to their higher fibre content.

Table 3 illustrates different starch levels of barley, oats, rice, and miscellaneous cereal grain sources. Polished rice portraits the highest total starch percentage (88%) and digestible starch percentage (74,7%) on a dry matter basis. However, it also includes the highest percentage of resistant starch (13,2%). Sources with high fibre content naturally show a lower content of starch, with oat fibre showing the lowest percentage of total starch (8,5%) and digestible starch (6,9%) on a dry matter basis.

Table 3. Total starch and starch fractions of whole grain, processed grain, grain coproducts, and other carbohydrate sources (Beloshapka et al., 2016).

Item	% DM Basis					
	FG [1]	TS	TS (w/o FG)	DS	DS (w/o FG)	RS
Barley category (Hordeum vulgare L.)						
Barley flake	0.08	67.7	67.6	63.9	63.8	3.8
Cut barley	0.13	74.2	74.1	67.0	66.9	7.2
Ground pearled barley	0.09	73.1	73.0	63.7	63.6	9.4
Malted barley	0.09	16.2	16.1	11.4	11.3	4.8
Pearled barley flakes	0.08	73.8	73.8	65.7	65.6	8.1
Steamed rolled barley	0.08	67.7	67.6	61.9	61.9	5.7
Whole pearled barley	0.11	72.3	72.2	64.9	64.8	7.4
Oat category (Avena sativa L.)						
Groats	0.10	73.4	73.3	69.5	69.4	3.9
Ground steamed groats	0.07	71.9	71.8	67.6	67.6	4.3
Instant oats	0.05	69.5	69.4	64.4	64.4	5.1
Oat bran #1	0.07	65.3	65.2	64.3	64.3	0.9
Oat bran #2	0.06	67.4	67.4	61.7	61.6	5.8
Oat fiber	0.08	8.5	8.5	6.9	6.8	1.7
Oat flour	0.06	69.2	69.2	65.6	65.5	3.7
Oatmeal (ground)	0.07	66.2	66.2	61.8	61.7	4.4
Quick oats	0.06	73.5	73.4	67.2	67.1	6.3
Regular rolled oats	0.05	68.7	68.7	65.0	65.0	3.7
Steamed rolled oat groats	0.06	71.2	71.1	66.1	66.0	5.1
Steel cut groats	0.06	68.4	68.3	68.2	68.2	0.1
Rice category (Oryza sativa L.)						
Brown rice	0.16	77.4	77.2	66.8	66.7	10.6
Defatted rice bran	0.06	34.2	34.2	29.8	29.7	4.4
Polished rice	0.06	88.0	87.9	74.7	74.7	13.2
Rice flour	0.48	73.6	73.2	66.8	66.4	6.3
Miscellaneous cereal grains and other carbohydrate sources						
Canary grass seed	0.17	49.7	49.5	47.3	47.1	2.4
Conventional whole millet	0.14	64.9	64.7	61.1	61.0	3.8
Conventional hulled millet	0.08	73.5	73.5	66.6	66.5	7.0
Conventional quinoa	1.31	55.7	54.5	53.3	52.2	2.4
Organic spelt hull pellets	0.16	42.0	41.9	38.3	38.2	3.7
Potato flake	0.49	73.2	72.8	66.9	66.5	6.3
Sorghum	0.20	70.5	70.4	63.3	63.1	7.2
Whole wheat	0.19	68.7	68.6	62.2	62.0	6.4
Whole yellow corn	0.24	65.0	64.8	65.6	65.3	0.0

[1] FG = free glucose; TS = total starch; DS = digestible starch; RS = resistant starch.

8.2 Fibre sources

Common sources of dietary fibre include beet pulp, powdered cellulose, pea fibre, and hulls derived from soybeans and peanuts. Meals made from various grains and oats also contribute with fibre, and additionally, an assortment of vegetables are increasingly integrated into dog food formulations.

Brans contribute with varying levels of fermentable and non-fermentable fibre, and the utilization of rice bran has surged in recent years due to its favourable content of fermentable fibre, essential fatty acids, and antioxidants. As well as providing a high palatability for the food (Spears et al., 2004). Pulp is a residue after processing of fruit and vegetables. Beet pulp is sourced from sugar beets, and contribute with a high content of fibre, predominantly insoluble (Fahey et al., 1990). Research indicates that incorporating beet pulp in pet food formulations positively influences bowel regularity and stool quality, contributing to gastrointestinal health through SCFA production (Sunvold et al., 1995b, 1995a). When incorporated optimally, the moderately fermentable fibre of beet pulp furnishes sufficient bulk for gastrointestinal functioning and supports gastrointestinal cell health without compromising palatability of the food.

Table 4 show some common types of fibre sources used in products formulated for weight loss, diabetes, and gastrointestinal disease. Cellulose and beet pulp is indicated to be a commonly used fibre. Hill's w/d (dry) includes the highest portion of crude fibre as fed (14,3%), and Hill's r/d (canned) includes the highest portion of crude fibre on dry matter basis (21,3%). The different gastrointestinal formulations from Royal Canin portraits the lowest crude fibre content as fed (1,5-2,3%), with gastrointestinal (dry) portraying the lowest content on a dry matter basis (1,7%).

Table 4. Fibre content of some canine commercial diets for weight loss, diabetes, and gastrointestinal disease (Chandler, 2016)

Table 2. Fibre content of some canine commercial diets for weight loss, diabetes mellitus and gastrointestinal disease

Manufacturer	Product	% CF as fed	% CF DMB	Dietary fibre as fed (DMB)	Main fibre sources	Calories/ 100g as fed	Calories /100g DMB
Hill's	r/d (dry)	12	13.1	–	Beet pulp, pea bran meal	302	approx 330
	r/d (canned)	5.2	21.3	–	Cellulose	72	297
	w/d (dry)	14.3	15.6	–	Cellulose, pea bran, beet pulp	299	approx 325
	w/d (canned)	3	11.3	–	Cellulose	95	360
Purina	CDO (dry)	6.5	7.1	–	Beet pulp	330	approx 360
Royal Canin	Gastro Intestinal (dry)	1.6	approx 1.7	3.52	Beet pulp	407	approx 445
	Gastro Intestinal (canned)	1.5	6	1.9 (7.6)	Vegetable fibres	109	436
	Gastro Intestinal Moderate Calorie (dry)	2.3	approx 2.5	7	Beet pulp	361	approx 395
	Gastro Intestinal Low Fat (dry)	1.7	approx 1.8	8.6	Wheat, barley, beet pulp	345	approx 380
	Gastro Intestinal Low Fat (canned)	1.7	6.5	2.9 (11.2)	Cellulose, beet pulp	92	354

CF = crude fibre, DMB = dry matter basis,
Note: diet formulae change, the numbers are an indication and may not be accurate. This table is intended as a reference guide only and is not exhaustive.

9. Comparison of different dog food formulations

As earlier discussed, dogs do not have a nutritional requirement for carbohydrates. In fact, in the wild, the diet of ancestral dogs consisted mainly of animal tissue, which is rich in fats and proteins, and low in carbohydrates. However, dogs can still derive certain benefits from the nutrient, especially during pregnancy and lactation, where female dogs may benefit from the quick release of energy for fetal development. Additionally, carbohydrates can serve as a convenient option for dogs engaged in activities requiring short bursts of energy, such as sprinting. Consuming carbohydrates also aids in sparing protein, which is beneficial in preserving muscle mass. By preserving protein and ensuring it's available for its primary functions rather than being used for energy, carbohydrates can contribute to improved physical performance and overall athletic abilities.

However, for dogs engaged in activities requiring sustained energy over long distances, a diet high in carbohydrates may present some disadvantages. This is because carbohydrates have a lower energy content per gram compared to fats, which are the preferred energy source for endurance activities. Therefore, relying too heavily on carbohydrates in the diet of long-distance athletic dogs may result in insufficient energy to support their performance and recovery needs.

Moreover, carbohydrates are often a cheaper source of energy compared to fats and proteins. It is abundant in plant-based ingredients, which often require less processing compared to protein and fat sources. For example, grains can be easily ground or milled into flour, while protein sources like meat may require more extensive processing, including cooking and rendering before being an ingredient in dog food.

In regular commercial dog food, the energy content derived from carbohydrates varies depending on the specific formulation of the product. Generally, carbohydrates contribute with around 30% to 60% of the total energy. However, it's important to note that manufacturers are not obliged to label the percentage of carbohydrates, so consumers often need to calculate this themselves by subtracting moisture, crude fibre, fat, protein, and ash from the analytical constituents of the food, and assuming the remaining fraction is carbohydrates. To further determine the fraction of metabolizable energy originating from the different energy-yielding nutrients, it’s necessary to calculate the calorie content. In human nutrition, Atwater factors are commonly applied to calculate metabolizable energy deriving from fat, protein, and carbohydrates with coefficients of 9-4-4 kcal/g, respectively. These factors are derived from an estimated digestibility coefficient of 96% for fat and carbohydrates, and 91% for protein.

However, when applying this for typical extruded pet food, these factors tend to overestimate the metabolizable energy, due to a lower ingredient digestibility in dog food. The National Research Council therefore suggested a lower digestibility coefficient of 80% for protein, 90% for fat, and 85% for carbohydrates. When adjusted for both digestibility and urinary losses, the Modified Atwater factors of 3,5-8,5-3,5 are reassigned for the calculations of ME values in dog food (Case et al., 2011j). While these values offer a more accurate approximation of metabolizable energy in dog food, they may still undervalue the ME values of easily digestible foods and overestimate the ME values of foods with significant fibre content.

To explore various carbohydrate sources and their inclusion levels in popular dog foods, a broad comparison is drawn among formulations tailored for medium adult dogs, weight control, sporting dogs, and mother/puppies. This encompasses dry extruded dog food, wet/canned dog food, and raw dog food varieties. The consumer price per kilogram is also provided, calculated based on similar packaging sizes to ensure a comparable pricing. However, the prices vary within the same product, and the lowest and highest available price online has therefore been used.

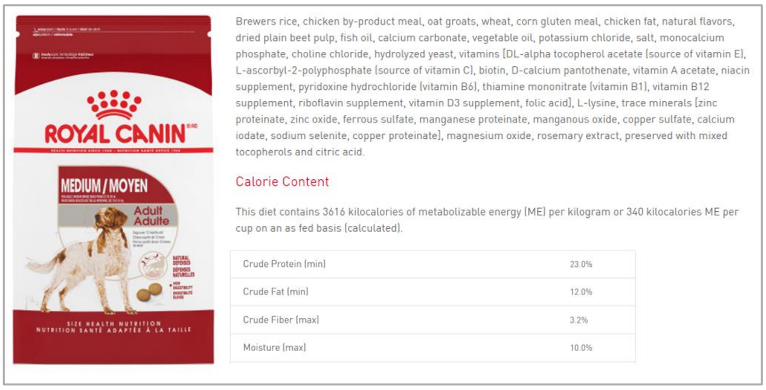


Fig.14. Ingredients and nutritional content of Royal Canin Medium Adult (Royal Canin, 2024a)

Royal Canin Medium Adult incorporates a variety of carbohydrate sources such as brewers rice, oat groats, wheat, corn gluten meal, and dried plain beet pulp. Although the ash content is unspecified, pet foods typically contain between 5-8% ash (Case et al., 2011j). Calculations are therefore done with a 5% ash content. It is estimated that this diet contains 50% carbohydrates, and 46,8% if fibre is excluded. This gives the formulation approximately 3462 kcal/kg in total, with 47% of the metabolizable energy deriving from carbohydrates.

Price: 899-1129 NOK/15 kg (approximately 60-75 NOK/kg)

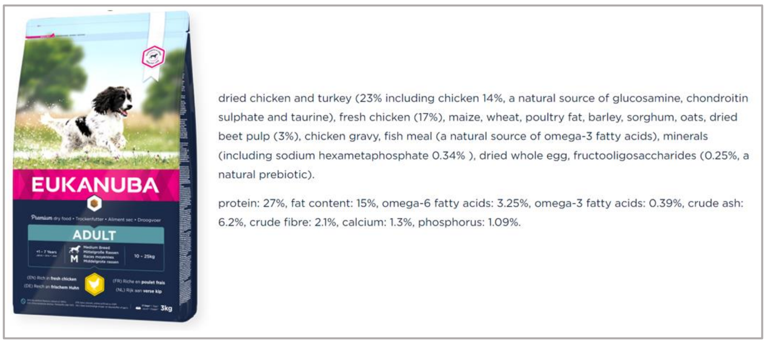


Fig.15. Ingredients and nutritional content of Eukanuba Adult Medium Breed (Eukanuba, 2024a)**.**

Eukanuba Adult Medium Breed includes maize, wheat, barley, sorghum, oats, and dried beet pulp as carbohydrate sources, along with some fructo-oligosaccharides. While moisture content isn't labelled, the moisture content in kibble typically ranges from 10-12%, and according to Case et al. (2011), moisture content generally doesn't exceed 10% post-drying (Case et al., 2011k). Calculations are therefore done on a 10% moisture content. It is estimated that this diet contains 41,8% carbohydrates, and 39,7% if fibre is excluded. This gives the formulation approximately 3600 kcal/kg in total, with 38% of the metabolizable energy deriving from carbohydrates.

Price: 949-1139 NOK/15 kg (approximately 63-76 NOK/kg)

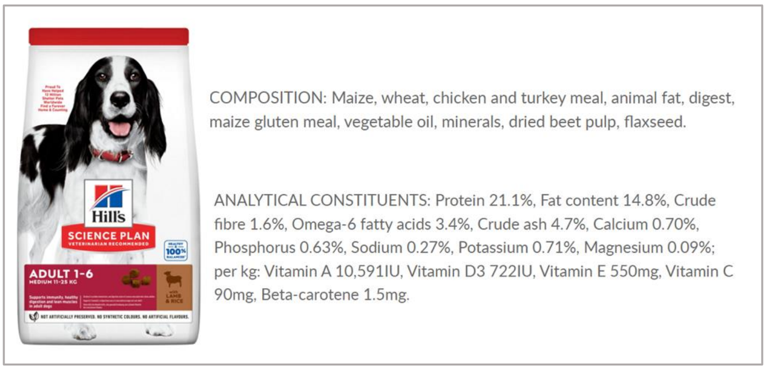


Fig.16. Ingredients and nutritional content of Hill's Science Plan Medium Adult Dog Food (Hills, 2024)

Hill's Science Plan Medium Adult Dog Food includes maize, wheat, maize gluten meal, and dried beet pulp as carbohydrate sources. Calculations are based on a 10% moisture content. The estimated carbohydrate content of this diet is approximately 49.4%, with 47.8% excluding fibre. This gives the formulation approximately 3669kcal/kg in total, with 45% of the metabolizable energy deriving from carbohydrates.

Price: 899-1039 NOK/14 kg (approximately 64-74 NOK/kg)

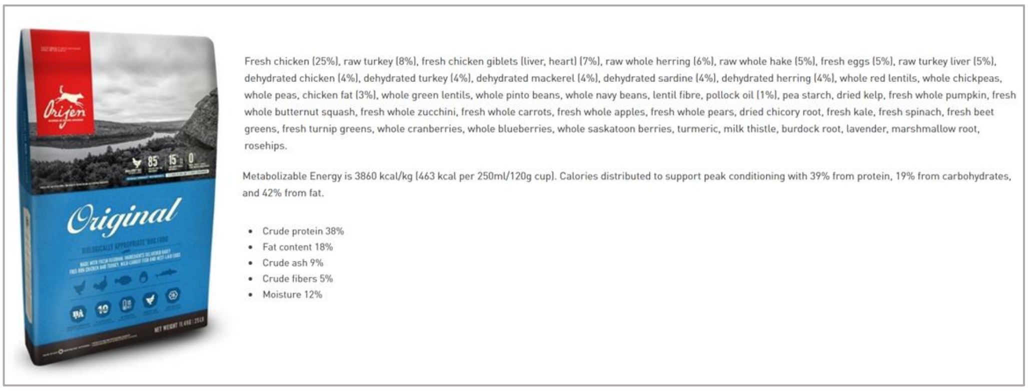


Fig.17. Ingredients and nutritional content of Orijen Original Dog Food (Orijen, 2024)

Orijen Original Dog Food features a diverse array of plant materials, likely serving as sources of both carbohydrates, protein, and vitamins. Examples include various legumes such as whole red lentils, chickpeas, peas, green lentils, pinto beans, and navy beans. Additionally, different vegetables and berries like pumpkin, squash, carrots, apples, pears, cranberries, and blueberries. Unlike the other diets, Orijen provides information about the metabolizable energy derived from carbohydrates, and calculations suggest this diet includes 23% carbohydrates, with 18% excluding fibre. Based on the provided calculations of metabolizable energy, it is evident that Orijen employs the general Atwater factors, rather than the modified Atwater factors. Which implies that the ingredients have a high digestibility in this formulation.

Price: 1090-1579 NOK/11,4 kg (approximately 96-139 NOK/kg)

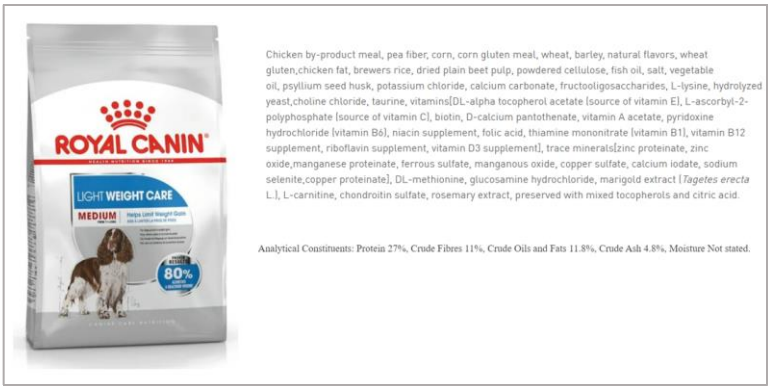


Fig.18. Ingredients and nutritional content of Royal Canin Light Weight Care (Royal Canin, 2024b).

Royal Canin Light Weight Care is formulated to regulate weight control. It features several sources of carbohydrates, including pea fibre, corn, corn gluten meal, wheat, barley, brewers rice, dried plain beet pulp, powdered cellulose, psyllium seed husk and fructooligosaccharides. These ingredients contain a large amount of fibre, which is evident in the analytical constituent of 11% crude fibres. The estimated carbohydrate content of this diet is calculated with a 10%

moisture content, and is approximately 46.6%, with 35.4% excluding fibre. This gives the formulation approximately 3187 kcal/kg in total, with 39% of the metabolizable energy deriving from carbohydrates.

Price: 929-1099 NOK/12 kg (approximately 77-92 NOK/kg)

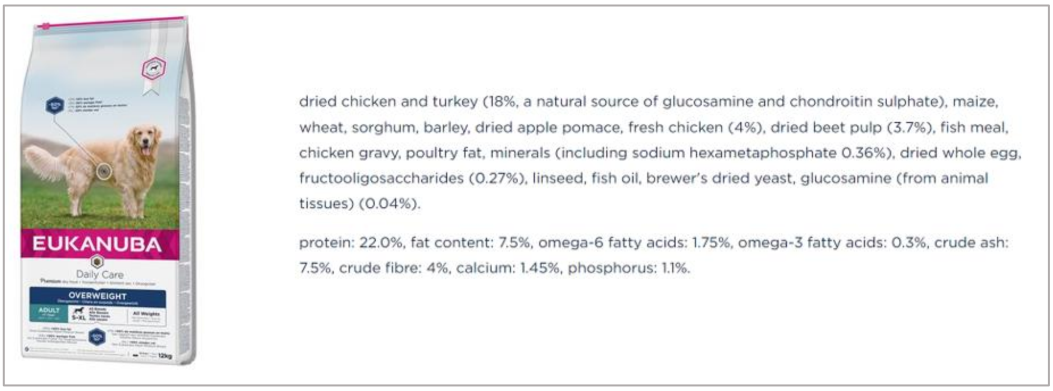


Fig.19. Ingredients and nutritional content of Eukanuba Daily Care Overweight Adult (Eukanuba, 2024b)

Eukanuba Daily Care Overweight Adult is formulated to regulate weight control. It includes several sources of carbohydrates: maize, wheat, sorghum, barley, dried apple pomace, dried beet pulp, and fructooligosaccharides. However, in contrast to Royal Canin, this formulation is lower in fibre content. The estimated carbohydrate content is approximately 53%, with 49% excluding fibre. This gives the formulation approximately 3122 kcal/kg in total, with 55% of the metabolizable energy deriving from carbohydrates.

Price: 784-959 NOK/12 kg (approximately 65-80 NOK/kg)

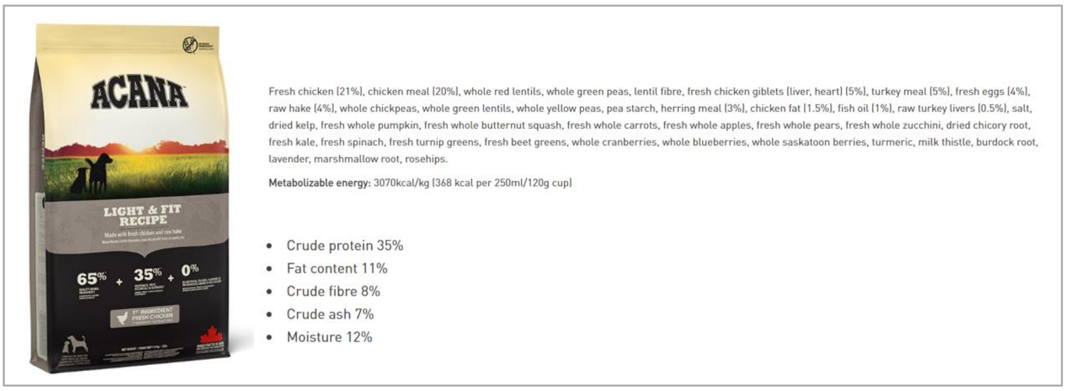


Fig.20. Ingredients and nutritional content of Acana Light & Fit Recipe (Acana, 2024)

Acana Light & Fit Recipe is also formulated to regulate weight control. It includes several sources of carbohydrates including various legumes such as whole red lentils, chickpeas, and peas, and different vegetables and berries like pumpkin, squash, carrots, apples, pears. The estimated carbohydrate content of this diet is approximately 35%, with 27% excluding fibre. This gives the formulation approximately 3105 kcal/kg in total, calculated with modified Atwater factors. However, Acana have provided information about the amount of metabolizable energy which is lower with 3070 kcal/kg. This implies that the digestibility of the ingredients in this formulation is lower. Approximately 30% of the metabolizable energy derives from carbohydrates.

Price: 784-1299 NOK/11,4 kg (approximately 69-114 NOK/kg)

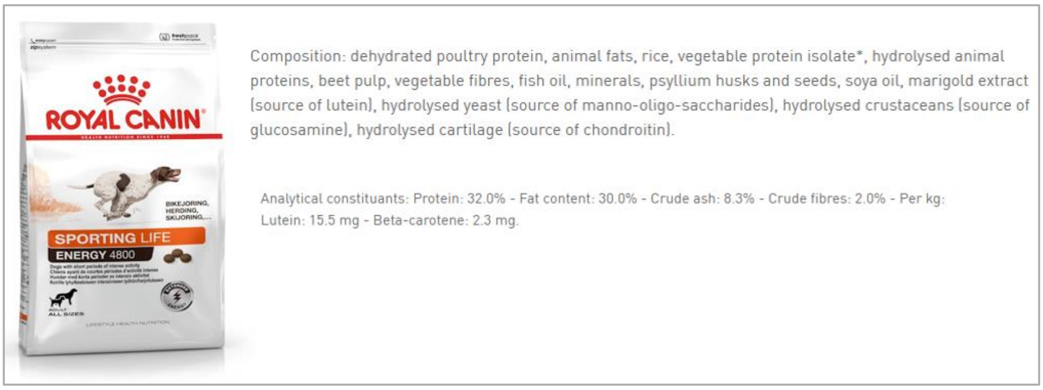


Fig.21. Ingredients and nutritional content of Royal Canin Sporting Life Energy 4800 (Royal Canin, 2024c)

Royal Canin Sporting Life Energy 4800 is formulated for adults with very long periods of sustained activity. It features several sources of carbohydrates, including rice, beet pulp, vegetable fibre, psyllium husks and seeds and hydrolysed yeast. The estimated carbohydrate content of this diet is calculated with a 10% moisture content, and is approximately 19,7%, with 17,7% excluding fibre. This gives the formulation approximately 4289 kcal/kg in total, with 14% of the metabolizable energy deriving from carbohydrates.

Price: 999-1209 NOK/13 kg (approximately 77-93 NOK/kg)

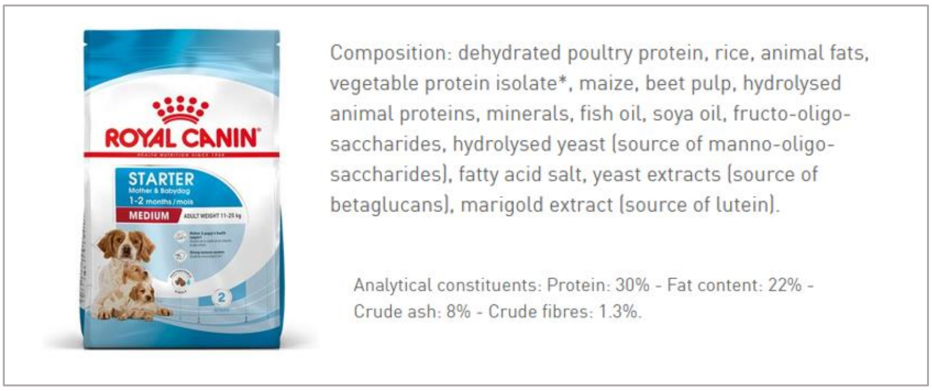


Fig.22. Ingredients and nutritional content of Royal Canin Starter Mother & Babydog (Royal Canin, 2024d)

Royal Canin Starter Mother & Babydog is formulated for the medium breed female at the end of gestation and during lactation, and for weaning puppies up to 2 months old. It includes a limited number of different sources of carbohydrates, including rice, maize, beet pulp and fructooligosaccharides. The estimated carbohydrate content of this diet is calculated with a 10% moisture content, and is approximately 30%, with 28,7% excluding fibre. This gives the formulation approximately 3924 kcal/kg in total, with 26% of the metabolizable energy deriving from carbohydrates.

Price: 1159-1249 NOK/15 kg (approximately 77-83 NOK/kg)

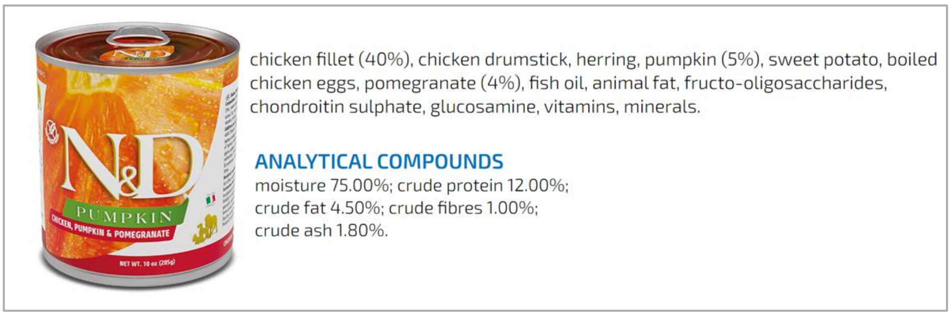


Fig.23. Ingredients and nutritional content of N&D Chicken, pumpkin & pomegranate (Farmina, 2024).

N&D Chicken, Pumpkin & Pomegranate is a grain-free wet/canned food which vegetables and fruits like pumpkin, sweet potato, and pomegranate. Compared to kibble, this diet has a higher moisture content. By calculations, it's estimated that this diet comprises 6.7% carbohydrates, with 5.7% excluding fibre. This gives the formulation approximately 1001 kcal/kg in total, with 20% of the metabolizable energy deriving from carbohydrates.

Price: 49-69 NOK/285g (approximately 172-242 NOK/kg)

Ingredients:

Contains 85% fresh meat, offal and bone.

British Chicken with Bone, British Beef Green Tripe, British Beef Kidney, British Beef Liver, Fresh Carrots, Fresh Butternut Squash, Fresh Broccoli, Fresh Green Curly Kale, Scottish Cold Water Salmon Oil, Organic Virgin Coconut Oil, Raw Sea Kelp Powder (Laminaria japonica), Bilberry Powder (Vaccinium Mytilus), Spirulina Powder (Spirulina platensis), Whole Milled Sesame Seeds, Wheat Germ Oil (natural vitamin E)

Typical analysis as fed:

- Moisture: 68.80%
- Protein: 12.70%
- Fat: 11.10%,
- Ash (inorganic matter): 3.70%,
- Fibre: 0.50%

Fig.24. Ingredients and nutritional content of Nutriment Chicken Adult formula (Nutriment, 2024)

Nutriment Chicken Adult formula is a grain-free, raw dog food, enriched with vegetables such as carrots, squash, broccoli, and kale. Similar to N&D's wet/canned food, this product also contains a high moisture content. By calculations, it's estimated that this diet comprises 3.7% carbohydrates, with 3.2% excluding fibre. Since fresh foods typically exhibit higher digestibility in studies compared to kibble, the standard Atwater calculations are recommended for raw dog food (Tanprasertsuk et al., 2021). Using Atwater factors, the calorie content is estimated to be approximately 1635 kcal/kg, with 8% of its metabolizable energy deriving from carbohydrates.

Price: 28 NOK/500g (approximately 56 NOK/kg)

ACTIVE complete dog food, also called no 33, is our high-quality basis food. This is one of our most popular mixes, together with ACTIVE complete dog food with salmon. The product is based on raw materials from chicken (meat cuttings, hide and bones), mixed innards, beef tripe and meat cuttings from pork and beef. If your dog is in need of any additional energy you can easily increase its daily amount.

Protein	15 %
Fat	19 %
Carbohydrates	0 %
Dry substance	35-39 %
Ashes	5 %

Fig.25. Ingredients and nutritional content of VOM Active Original (VOM, 2024)

VOM Active Original is a grain-free, carbohydrate-free, raw dog food made in Norway. The moisture content of this food is 61-65%. Using Atwater factors, the calorie content is estimated to be around 2310 kcal/kg, providing the dog with 0% of its metabolizable energy from carbohydrates.

Price: 399-440 NOK/18 kg (approximately 22-25 NOK/kg)

Table 5 illustrates the grams and total cost calculations of various dog food formulations for a dog requiring 600 kcal per day. While most formulations exhibit relatively similar costs, two options stand out as the most expensive and cheapest alternatives. VOM Active Original emerges as the most economical choice, while N&D Chicken, Pumpkin & Pomegranate stands out as the priciest option.

Table 5: Grams per day and NOK per 600 kcal of the different food formulations

Formulation	Grams per day	NOK per 600 kcal
Royal Canin Medium Adult	174 g	10-13
Eukanuba Adult Medium Breed	167 g	10-13
Hill's Science Plan Medium Adult Dog	164 g	10-12
Orijen Original Dog Food	155 g	15-22
Royal Canin Light Weight Care	188 g	15-17
Eukanuba Daily Care Overweight Adult	192 g	12-15
Acana Light & Fit Recipe	195 g	13-22
Royal Canin Sporting Life Energy 4800	140 g	11-13
Royal Canin Starter Mother & Babydog	153 g	12-13
N&D Chicken, pumpkin & pomegranate	600 g	103-145
Nutriment Chicken Adult formula	367 g	21
VOM Active Original	260 g	6-7

Because moisture content varies across formulations, the nutrient concentration varies as well. Table 5 clearly illustrates those formulations with higher moisture require a larger quantity of food to supply the same energy. Dog owners should take this into account when comparing prices of different foods. To illustrate, a standardized calorie amount of 600 was chosen to showcase the grams required from each formulation to potentially fulfil the dog's energy requirements.

9.1 Comparison and evaluation of the foods

A comparison of the different dog foods reveals a wide range of carbohydrate sources, inclusion percentages, and pricing across various brands and types of dog food.

The variation in carbohydrate sources across the different food formulations underscores the diversity in feeding strategies employed by pet food manufacturers. Some diets, such as Royal Canin Medium Adult and Hill's Science Plan Medium Adult Dog Food, utilize traditional carbohydrate sources like grains (e.g., maize, wheat) and beet pulp, while others like Orijen Original Dog Food opt for a wider array of plant materials including legumes, vegetables, and berries. The wet/canned and raw food formulations are commonly grain free, and include vegetables and fruits like pumpkin, sweet potato, and pomegranate. The raw dog food formulation from VOM is totally carbohydrate-free.

Furthermore, the estimated carbohydrate content varies significantly among the diets, ranging from as high as approximately 50% in Royal Canin Medium Adult, Hill's Science Plan Medium Adult Dog Food and Eukanuba Daily Care Overweight Adult, to as low as 3.7% in Nutriment Chicken Adult formula and 0% in VOM Active Original. Fiber content, which is often included in carbohydrate calculations, also varies among formulations, with some products containing higher fibre levels than others. These formulations are tailored for weight management. This variability highlights the importance of considering individual dietary needs and health goals when selecting a dog food.

The information provided on the labels also brings attention to the methods used for estimations of metabolizable energy. While one diet provides information of the energy derived from carbohydrates, others require calculations. There are probably also large differences in the digestibility of the various ingredients in the foods, as Orijen has chosen to use general Atwater factors to calculate metabolizable energy. On a general basis, this variability in available data underscores the need for standardized labelling within the pet food industry to provide consumers with transparent and easily comparable nutritional information.

Moreover, the difference in moisture content of wet/canned foods compared to kibble will affect the concentration of nutrients, including carbohydrates, and must be considered when evaluating the overall nutritional adequacy of a diet. As demonstrated in Table 5, the quantity of wet/canned and raw dog food required to deliver the same energy content as dry food will be greater due to the less compact nature of nutrients in wet/canned options.

Prices exhibit significant variation across different formulations and brands, ranging from approximately 22 NOK/kg to 242 NOK/kg. While raw dog foods typically carry a reputation for being pricier per kilogram compared to traditional dry or wet/canned dog foods, our comparison reveals that VOM Active Original emerges as the most economical option at 22 NOK/kg, with N&D Chicken, Pumpkin & Pomegranate representing the priciest alternative. This price discrepancy may be attributed to the smaller package size of the wet/canned option compared to other formulations, influencing the final cost outcome. It's a common misconception that the most expensive food formulation equates to the highest quality, and vice versa for the cheapest option. While plant-based materials generally tend to be cheaper than animal-based ones, in this instance, VOM Active Original, despite containing no plant-based materials, emerges as the most affordable choice. This can be attributed to factors such as its Norwegian production origin, utilizing exclusively Norwegian raw materials, thereby avoiding additional costs associated with international transportation and taxes. Consequently, Norwegian dog owners benefit from access to a competitively priced food with high percentages of animal-based ingredients.

In conclusion, the comparison of carbohydrate content among different dog foods highlights the importance of individualized dietary considerations, transparent labelling practices, and ongoing research to ensure optimal nutrition and health outcomes for dogs. Pet owners and veterinarians should carefully evaluate factors such as carbohydrate sources, content, and energy distribution when selecting a diet to meet the specific needs of their canine companions.

10. Overall conclusions

The existing literature and research suggest that dogs are adapted a carnivorous diet, primarily due to their anatomical and physiological characteristics making them adept to digest animal derived nutrients, such as fat and proteins, rather than carbohydrates. Dogs do not have a dietary requirement for carbohydrates, because they can synthesize glucose form non-carbohydrate precursors found in fat and protein. Carbohydrates are therefore not considered an essential nutrient. However, it is important to recognize that dogs with high energy requirements, such as those engaged in intense physical activities, gestation, or lactation, can benefit from carbohydrates as a readily available energy source. Furthermore, in cases where dogs experience conditions like diabetes or obesity, the incorporation of fiber with a low glycemic index can prove beneficial. However, dogs performing endurance work, such as sled dogs, may encounter challenges with carbohydrates in their diet. Both because carbohydrates provide less energy compared to fat per gram, and because research indicates that a high-carbohydrate diet may lead to stiffness in gait and muscle fatigue.

An examination of various dog foods reveals significant differences in the inclusion of carbohydrates for dogs. This discrepancy extends not only to the source of carbohydrates—ranging from grains, legumes, vegetables, and berries—but also to the percentage included in the formulations. While kibble formulations generally contain an average level of 40-50%, wet/canned and raw formulations consistently exhibit carbohydrate levels of less than 10%, with some formulations containing zero carbohydrates.

Such variability should influence the pricing of dog foods, as carbohydrate ingredients are generally perceived as a less expensive compared to animal-derived ingredients. However, upon comparison, the formulation with zero carbohydrates were found to be the less expensive alternative, priced at over half the cost of general kibble options. Speculation on the reason for this can only be made, but it is worth noting that the brand, called VOM, is produced in Norway and advertising the use of exclusively Norwegian animal raw materials. This could provide an advantage because of reduced transportation costs across national borders and favourable tax conditions in the Norwegian market.

The priciest choice among the options is the wet/canned food. This preservation method typically yields smaller packaging sizes, likely contributing to its comparatively higher price range. Furthermore, it boasts a higher proportion of animal-derived ingredients, with a reduced carbohydrate content, which on a general basis is perceived to make the food more expensive.

In summary, the accumulated knowledge underscores the complexity of canine nutrition, emphasizing the necessity for tailored dietary approaches that consider individual needs and circumstances. While dogs exhibit carnivorous tendencies, the inclusion of carbohydrates, particularly in specific contexts, can offer valuable nutritional advantages. Considering the foods examined in this study, it is evident that pricing can vary significantly depending on the formulation. This factor should also be considered when selecting the most suitable food for the dog.

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