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Review Article

Dietary Transitions Toward Sustainable Horse Feeding

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A B S T R A C T

Sustainability is the balancing act of optimizing the use of current resources without compromising the current or future environment. Within the agriculture sector the primary focus of sustainability has been to reduce environmental pollution, specifically greenhouse gasses (GHG) emissions, nitrogen emissions, and leaching. For the equine industry the first step towards sustainability is the documentation and critique of current feeding and management practices to permit modifications to enable the industry meet social and legislative obligations. As a monogastric hindgut fermenter on a per kg bodyweight basis the horse has relatively lower GHG emissions compared to ruminants. However, there are several opportunities to further reduce the environmental impact of the equine industry. The majority of these relate to subtle changes, or consideration of, improving feed conversion, using alternative ingredients, and management of fecal material associated with intensive husbandry. To initiate the journey towards sustainability this review documents opportunities with current equine feeding and management practices to reduce the environmental impacts of the equine industry.

1. Introduction

In 2015, the United Nations adopted a set of Sustainable Development Goals (SDGs) that imagined a future (2030) without poverty and hunger, and safe from the worst effects of climate change and loss of biodiversity [1]. The United Nations defined sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.” Sustainability is often conceived of in terms of three dimensions: environmental, economic, and social which is sometimes referred to as the triple bottom line. The animal nutrition industry’s sustainability efforts contribute to a variety of SDGs, including No. 2, Zero Hunger, No. 3, Good Health and Well-Being, No. 12, Responsible Consumption and Production, No. 13, Climate Action, No. 14, Life Below Water, and No. 15, life on land. Currently, nearly 140 developing countries around the world are trying to meet their development needs without negatively impacting future generations [1].

The predominant focus on sustainability in the agriculture sector has been the impact of the production system on the environment. Nutrient loss, particularly nitrogen, and phosphorus were the first aspect of the environmental impact of agriculture to be quantified and included within a regulatory framework. In recent years there has been increasing focus on the contribution of the agriculture industry to the production of greenhouse gases (GHG: including methane CH4, hydrogen H2, carbon dioxide CO2) rather than just nutrient leaching. Globally the livestock industries, including horses, account for approximately 18% to 20% of global greenhouse gas emissions [2]. Methane emissions from ruminant livestock have been identified as the primary contributor to greenhouse gas emissions within the agriculture sector, and this has resulted in a shift in research focus from methane as an energy loss to methane emission reduction [3]. The large research and regulatory focus on ruminants and methane production reflects the numerical over representation of ruminants within the production livestock species. Ruminants also have greater relative methane emissions per animal, and on a per kg live weight basis than monogastric livestock [3–5]. Ruminant methane emissions from enteric fermentation account for a significant proportion of methane emissions production globally compared to the other animal species, as shown in Table 1. Horses as a monogastric hindgut fermenter are relatively efficient at digesting protein and emit less methane than ruminants. This in combination with the relatively

Abbreviations: SD, standard deviation.

Ethical Statement: There are no human/animal subjects in the article and informed consent is not applicable.

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Table 1
Examples of comparative methane emissions reported for the USA, European Union, and South Africa for enteric fermentation from the main livestock categories (emission unit Tg).

Country	Total Emission Tg/ Year	Beef Cattle	Dairy Cattle	Sheep	Goat	Donkeys and Mules	Pigs	Horses	Ref.
US	139.8	33.2	99.6	1.0	0.3	-	2.1	3.6	[6]
EU		3.3	2.9	0.7	0.09	0.002	0.1	0.09	[7]
South Africa	1.2	0.8	0.08	0.2	0.03	0.001	0.002	0.005	[8]

Abbreviation; Tg, tera grams.

small horse population size compared to cattle and sheep means that little legislative or research attention has been paid to the equine industry in relation to GHG emissions, or even sustainability in the wider context.

The horse is economically and socially significant within the European Union with an estimated 6 million horses residing in the 27-member states [9]. However, to date, horses are frequently not included, or considered, in the sustainability framework, in part because their primary use is for sport [10,11]. However, because of the management systems and the feedstuffs consumed, the horse fits firmly within the agriculture sector.

The equine industry's major environmental impact, and thus its sustainability focus, relates to horse feeding. Nutrition is an important aspect of horse keeping that can have an impact on the environment from feed production through to manure disposal [12]. However, information on management systems and the environmental impact of horse keeping is still limited, and there is limited external pressure for increased documentation as this industry is not typically included in environmental planning [13].

In association with limited data on management practices there is also a lack of information on the fundamental principles of sustainable feed management in relation to horse feedstuffs. Improving the feed conversion rate would theoretically require less feed to meet the nutritional needs of horses. Therefore, understanding the horse's gastrointestinal tract, specifically the hindgut microbiota, is a logical starting point for horse nutrition's contribution to sustainability, followed by the effects of the different nutrient sources including carbohydrates, proteins, fats, and feed additives. This review assesses how changes in dietary carbohydrates, proteins, fats, and supplements might impact the environmental impact of horses and the horse industry. The goal of this review is to provide comprehensive information documenting the potential impact of horse feeding on the environment through their diet, in order to raise awareness and understanding within the equine sector.

2. Horses Gastrointestinal Tract

Horses are classified as a nonruminant herbivore, or more specifically as a monogastric hindgut fermenter. The horse's digestive system is divided into two parts: the foregut (stomach and small intestine) and the hindgut (cecum and colon). The digestive system of horses evolved to maximize digestion of a relatively high fiber forage diet. As a nonruminant herbivore, the horse adapted to a high-fiber, low-starch diet by foraging daily for long periods (approx. 16 hours per day) [14]. To obtain nutrients, horses use both enzymatic digestion in the small intestine (primarily for the digestion of soluble carbohydrates and protein) and microbial fermentation of fiber in the hindgut [15,16].

The stomach, as in other species, is the first site of digestion. In the horse, the stomach accounts for approximately 8% of total digestive tract capacity [17], while the small intestine and hindgut account for 30% and 61% percent, respectively [18–20].

The evolutionary niche of the horse has resulted in a gastro intestinal track optimized to exploit an almost continuous supply of low volumes of high fiber forage. Modern, or intensive, management systems often provide, in contrast, few feeds of higher volume, and in some cases relatively large quantities of concentrates or soluble carbohydrates [21]. The limited relative size of the horse's stomach and small intestine, coupled with an inability to vomit, means that feeding fewer larger meals, as is common practice in modern management systems, predisposes the horse to having quantities of feed that exceeds the foregut's capacity, resulting in undigested carbohydrate and protein entering the hindgut and undergoing rapid fermentation. This fermentation of the undigested carbohydrate can have negative health consequences for the horse through changing the microbiota and pH in the hindgut. Undigested protein that bypasses enzymatic digestion in the small intestine and enters the lower digestive tract is fermented by the microbiota, which produces microbial protein that is not efficiently absorbed, resulting in higher levels of N in manure [22,23], and thus greater potential for nitrogen leaching and methane production from fecal material.

3. Hindgut Microbiota and Implications for Feed Digestion

The carbohydrate, protein, cellulose, fiber, hemicellulose, and starch content of the diet will degrade at different rates in the hindgut, yielding different products after fermentation, such as microbial protein, volatile fatty acids (acetate, propionate, butyrate), CH4, and other iso-acids [24–27]. The genera and species composition of the microbiota of the hindgut will reflect the differing availability of these substrates [3].

The production of volatile fatty acids in the horse's hindgut via fiber fermentation can generate up to 60% of the daily digestible energy requirement. These volatile fatty acids are produced by symbiotic microbiota during the fermentation of plant-based fiber in the horse's diet [28–30]. These symbiotic microbiota in the hindgut (caecum and colon) appear to be unique to each animal and respond quickly to dietary changes [28,31,32]. The relative proportions of protozoa, fungi, and bacteria in the microbiota reflect the gastrointestinal tract's health, the type of forage consumed, and the location within the hindgut from which the microbiota was sampled [33] Within the literature examples of the effect of feed substrate change particularly, forage to grain include the rapid increase in amylolytic bacteria associated with changing from predominately Alfa diet to a concentrated diet [34] or the significant increase in lactobacilli and streptococci concentrations after abrupt incorporation of barley into a fiber-based diet [28,29]. Thus, hindgut fermentation is most efficient when the horse has constant access to forage and limited access to feeds that could alter the pH of the cecum, such as large grain meals [35,36].

Total digestion time (time from ingestion to defecation) is frequently measured as transit time using a marker and varies greatly depending on the amount of feed offered and the relative fiber content of the feed offered, with high fiber forage typically having a longer transit time to allow for effective fermentation. Even when the feed type and quantity offered are consistent, there is some variation in transit time between horses. Transit time from intake to defecation is generally reported to be between 36 and 72 hours, with transit times of around 24 hours being common for horses fed fresh pasture [35].

Feed quality and quantity influence the microbiota of the equine hindgut. Feed quality encompasses all aspects of a feed that are influenced by treatment, storage, conservation, hygiene, and the content of specific substances have an impact on the microbiota of the equine hindgut. Even a late harvest due to weather conditions can have an impact on straw feed quality and, as a result, methane production [27]. Access to pasture may provide a greater diversity in the feed on offer (through diversity in pasture species and the respective macro nutrient profile) and this is reflected in the number of operational taxonomic units (OTUs) identified when horses were at pasture compared to stabled and offered conserved forage [35]. Cut pasture offered to horses stabled had a similar number of OTUs to horses offered conserved forage when stabled, indicating the role feed supply and transit time may have on the diversity of the microbiota. The microbiota can respond to changes in both feed supply and quality in a relatively short time frame with changes in the relative abundance of the dominant phyla observed with the first markers associated with the change in diet, approximately 11 hours post diet change [35]. These data demonstrate the importance of hindgut microbiota health in relation to the efficient fermentation of feedstuff and minimization of the potential for nitrogen leaching and methane production from fecal material.

4. Environmental Impact of Current Equine Nutrient Management

The nutrition of the horse and the management system are heavily inter-related. The management system in place often reflects the level of activity (from top level sport to low level sport and recreation) and local environmental constraints (seasonal variations that require housing to avoid adverse weather events). In Western Europe and the Americas there is a ∼ 3:1 ratio in the number of recreation / pet horses to those registered for sport and racing [37]. From this figure we can estimate that ∼25% of the equine population in these countries are in some form of intensive housing or management system, with the remaining 75% utilizing a pasture-based or partly pasture-based management system.

Across countries the management of the horses used in sport appears to be relatively homogeneous [38], even in countries with temperate climates [39]. The consistency of the intensive management system means that sustainability issues relating to nutrition and the management and disposal of manure and soiled bedding material are consistent across countries. There is greater variation in the pasture-based management systems used across countries, due to variations in climate [10,33,40] and this variation is further exacerbated by some of the horses in the recreation / pet category being thrifty phenotypes managed by feeding higher fiber, lower digestible energy (DE) forage.

Diets high in fiber have a similar inflationary effect on methane production in horses as observed with increased fiber and methane produced via rumination. However, in contrast to ruminants, the horse as a hindgut fermenter releases less methane into the environment as a direct result of feed fermentation. The primary source of methane production from horses is from feces, specifically the postexcretion degradation of the organic components within the feces, which are generally carbohydrates, proteins, and lipids. Anaerobic degradation of animal manure produces biogas, which is primarily composed of methane and carbon dioxide [41]. At pasture there is dispersion of the urine patches and the fecal piles which helps minimize the level of CO2 and CH4 released during degradation. Intensive management of horses requires disposal of bedding and fecal material. The storage of fecal material, and the natural degradation occurring within these manure stockpiles accentuates the CH4 emissions [42]. Table 2 presents the published values for GHG emissions from fresh and stored horse manure.

Overfeeding is an inefficient use of resources that increases the nutrient content of the manure, increasing the potential for methane production via anerobic degradation. Overfeeding may be a relative common practice in sport horses but perhaps more common in pet and recreation horses. If horse obesity is used as a proxy for overfeeding then somewhere between 20% and 45% of the pleasure / recreation sector of the equine industry may be overfeeding their horses [45,46]. This obesity problem and overfeeding may be compounded by the finding that many owners often perceive their horses to have body scores lower than those allocated by researchers and veterinarians [47,48]. The relative impact of overfeeding on methane production is determined by the feedstuff used, as this alters the concentrations of nutrients transferred to the manure [12]. Manure methane production can be calculated theoretically in terms of volatile solids (VS). The VS estimated from different batches of horse manure appears to be variable, ranging from 68 to 273 mL/g [49]. The variation between batches could be due to differences between horses, but it could also be due to differences in the diet composition of horses of different ages and workloads. Despite this variation, even the upper range of the estimated values for horses are lower than those reported for pig manure (516 l–530 l kg1 VS) and cattle (469 l kg1 VS) [50].

In association with the trend of over feeding many horse rations contain excess crude protein, in some cases up to 165% of the NRC recommendations [51]. Excess crude protein is excreted in feces and urine as nitrogen (N) potentially increasing the nitrogen leaching risk. With housing the N is contained within the manure and bedding discarded, and prevention of N leaching then is dependent on storage and degradation of this material. However, some phenotypes, such as ponies, can be over-fed and receive excess nitrogen even when at pasture. In countries with temperate climates like New Zealand and Australia, many horses within the recreation and leisure category are kept at pasture 24/7, and have continuous access to pasture with a higher protein content. Given the preferential spatial distribution of feeding, defecation, and urination areas within horse pastures, there may be specific “hot spots” in paddocks and pastures [52]. Set stocking horses appears to amplify the location of these preferential areas for grazing and latrine areas. Data from the provision of pasture turnout and feeding in Nordic countries has identified greater potential for N loss, during the spring melt, in the areas associated with the greatest concentration horses, and thus feces and urination, often near sites associated with the provision of supplementary forage [53]. At present, there is currently insufficient data to suggest that for horses managed at pasture that the focal latrine areas on a *per ha* basis leads to greater N leaching potential than herbivores with a more dispersed urination and defection pattern.

The majority of domestic horses in Europe spend at least some of their time in stalls or loose boxes, the by-product of this is the need to manage and dispose of manure and bedding. Manure storage, particularly in relation to horses in housing systems, can have a significant impact on nitrogen leaching potential. The main danger of stored manure, such as manure piles, is that if not protected from rain and runoff, these can result in N leaching into the environment [54]. In the case of housing, not only manure but also used bedding is frequently stockpiled for degradation or transported offsite for use in products such as garden compost, etc. The bedding material used during housing may affect VS estimates and, in some cases, nitrogen methane production. Straw appears to be a poor choice for horse stall bedding in terms of methane production during subsequent degradation. The VS from straw as mixture with manure degradation was estimated to be equivalent to values calculated for horse manure alone (54–289.5 mL / g VS) [50]. Soft wood-based bedding, on the other hand, appears to dilute VS production, and the effect of this dilution increases with an increasing

Table 2
The published values for GHG emissions from fresh and stored horse manure.

Type of Horse Dung	Nitrous Oxide (N_2O)	Nitric Oxide NO	Nitrous Acid HONO	Methane (CH_4)	Ref.
Horse dung (mean)	182 µg N_2O–N m^{-2} h^{-1}	52 µg NO–N m^{-2} h^{-1}	_	_	[43]
Fresh dung (mean±SD)	Variable	56 ± 22 ng N kg dw^{-1} h^{-1}	35 ± 19 ng N kg dw^{-1} h^{-1}	20.8 ± 4.1 µg g dw^{-1} h^{-1}	[44]
One month old dung (mean ± SD)	_	900 ± 77 ng N kg dw^{-1} h^{-1}	53 ± 20 ng N kg dw^{-1} h^{-1}	10.0 ± 3.3 µg g dw^{-1} h^{-1}	[44]
One year old dung (mean ± SD)	20.3 µg g dw^{-1} h^{-1}	3000 ± 670 ng N kg dw^{-1} h^{-1}	113 ± 34 ng N kg dw^{-1} h^{-1}	0.61 ± 2.4 µg g dw^{-1} h^{-1}	[44]

Abbreviation: SD, standard deviation;
Cells with empty (–) values were not tested in a given study.

Table 3
The published values of nitrogen emissions in horse excretions (manure and urine) and the management and storage variables influencing these.

Factors	Total Nitrogen (N) Value in Horse Dung	Ref.
Exercise		
Sedentary horses	2.3% dry basis	[55]
Very active horses	3.2% dry basis	[56]
Stable bedding material		
Without bedding	1.72 % dry basis	[57]
With bedding	2.04% dry basis	[57]
Organic bedding	1.34% dry basis	[58]
Straw	0.10% total solids	[59]
Rye straw	0.06% total solids	[59]
Sawdust	0.10% total solids	[59]
Mostly straw some sawdust	0.3% total solids	[60]
Woodchip and sawdust	0.9% total solids	[61]
Turnout duration		
Pasture (separate) for 2 h–5 h	7.2–19.2 g per day	[62]
Pasture (separate) for 6 h–24 h	24.0 g per day	[62]
Free-range stable all day	7.1 g per day	[63]
Mudpaddock (separate) several h	7.2 g per day	[64]
Pasture space allowances		
Pasture space allowance <200 m^2 (mean ± SD)	50.59 ± 15.71 kg per hectare	[65]
Pasture space allowance ≥200 m^2 (mean ± SD)	−7.69 ± 5.08 kg per hectare	[65]
Feed choices		
Optimum diet (mean ± SD)	0.242 ± 0.01 ppm	[66]
high protein diet (165% of the recommended protein amount) (mean ± SD)	0.278 ± 0.01 ppm	[66]
Haylage-only diet	51.6 g N in feces/day and 104 g N urine /d	[67]
Hay-only diet	51.4 g N/day in feces/day and 64 g N urine /d	[67]
Hay and oat diet	43 g N/day in feces/day	[67]
Hay and linseed diet	48 g N/day in feces/day and 105–111 g N in urine /d	[67]
Season		
Wintertime (mean ± SD)	31.22 ± 12.01 kg per hectare	[65]
Summertime (mean ± SD)	−14.81 ± −4.24 kg per hectare	[65]
Housing		
Group housing (mean ± SD)	−5.30 ± 5.35 kg per hectare	[65]
Single housing (mean ± SD)	19.46 ± 11.25 kg per hectare	[65]

ratio of shavings to mature (up to a 4:1 ratio) [49]. Table 3 presented the values of nitrogen emissions in horse excretion associated with influencing factors such as the pasture turnout, the level of exercise or the bedding material used.

After aggregating and averaging the published data on methane production by horses, the IPCC calculated an enteric fermentation factor for horses of 18 kg of CH4 per horse per year [68]. The enteric fermentation factor varies depending on the type of feed used and the management system in place. Using values calculated for similar regions and management factors (feed and housing), annual methane production estimates for horses were less than half of those for nondairy cattle of similar bodyweight (57 kg CH4 / year).

Despite a low enteric fermentation factor for individual horses, the number of horses kept for sport and recreation in Europe and North America continues to grow, resulting in a relative increase in the impact this sector has on sustainability. Due to the horse's primarily nonproduction or noncommercial role, with the majority of horse owners perceiving their horse as a companion animal rather than livestock [69], the return on investment for the owner is based on marginal utility rather than financial return. Thus, similar to the situation observed with companion animals (such as dogs and cats) the expenditure on feed, consumables, and accessories is frequently less constrained by cost than observed with production livestock. This does present an opportunity within the equine industry's sustainability framework to consider feeding and management practices that reduce the environmental footprint without cost being a major or the primary constraint.

When considering sustainability within the equine sector it is common to focus on the more obvious or immediate environmental effects, such as nutrient leaching and pasture erosion. However, the wider impact of management practices such as transportation and nonrecyclable packaging of many commercial feedstuffs must be considered. Many in the equine industry find it difficult to easily quantify the environmental impact and sustainability of variables related to feed production, transportation, and use of energy, resources (e.g., plastics), land, pesticides (herbicides, fungicides, and insecticides), and fertilizer (N, P, and K), gaseous emissions (CH4, CO2, N2O, CFC, NH3, NOX, SO2), and plant nutrient leaching (NH3, – NO3, PO4). The difficulty in quantifying these may explain why they may not always be at the forefront of owners' feed purchasing decisions.

5. Impact of Specific Feedstuffs

5.1. The Role of Carbohydrates

There is a link between CH4 output and fiber concentration in the diet, especially when the fiber is difficult to digest, such as acid detergent fiber [3,70]. If the sole goal is to reduce methane emissions, horse owners should be encouraged to provide feed with a lower fiber content, even if this is not ideal for gastro intestinal health [31,71–74]. The recommendation is to meet the minimum fiber requirement of 1.5kg DM/kg bw for horses [75] and avoid the overconsumption or ad libitum forage access [44]. However, given the inherently low annual methane production per horse, or per kg bodyweight for horses, it may be better to focus on other aspects of sustainability associated with the production of horse feed.

Feeding and management considerations vary depending on the horse's age, weight, workload, and growth rate. There are some differences in feeding practices between countries, but the general trend is that forage should be the foundation of the horse's diet, with concentrates (soluble carbohydrate) used to increase the energy density of the forage base [76]. Forages such as hay and/or pasture grasses and legumes are traditional cornerstones of horse rations in most countries such as United Kingdom, Germany, Australia, Turkey, and United States [71,77–79] . Oats, barley are the grains most frequently provided as a concentrate within the ration. Oats and Barley are also frequently included along with grains such as corn, milo, wheat, rice, and rye within formulations of commercial (pelleted) feeds [76,80,81].

In comparison to exercised horses, sedentary horses are typically fed a forage-based diet. The challenge for horses in this category, which also includes pet and recreation horses, is that they are frequently thrifty phenotypes with a low daily digestible energy requirement. As replacement of all or part of the forage with extruded or processed grains is not a viable option, reducing the acid detergent fiber (ADF) component of the diet represents one of the few mechanisms to reduce CH4 production. The substitution of silage for hay, which has a lower ADF, may provide a mechanism for reducing methane potential [82,83]. However, the silage (haylage) may have a DE value up to 1/3rd more than the hay, which may represent a significant increase in DE offered for thrifty phenotypes. If these horses are housed, this may create a management challenge because one mechanism for reducing boredom and the prevalence of stereotypic behaviors is to provide constant access to forage, which if not high in fiber and low in DE may result in obesity in these horses.

Despite geographical differences, the management of sport horses appears to be very consistent [71,79,81,84–86]. In most countries, the phenotype and genotype of the horses used are consistent, as is the feeding of a forage-based ration supplemented with grains and concentrates to increase the energy density of the ration [79,84,85] and a number of different supplements [71,87,79]. Unprocessed grain feeding is now relatively uncommon in the racing industry, with most trainers now offering concentrates in the form of balanced concentrate feeds (premixed feeds [21]. In sport horses, this pattern of providing concentrates from premixed feed is also observed [39,77,84].The advantage with this trend is that commercial feeds often contain grains or grain by-products that have undergone processing such as extrusion or milling that will increase the possibility of prececal digestion and may help reduce CH4 production.

Substitution of roughage with concentrate feed does not represent a viable long-term option to reduce methane production from horses. Primarily the generation of methane is low, so there is a limited impact at a per animal level. Secondary to this gastro intestinal health is dependent on the horse receiving sufficient roughage (fiber) within the diet. Roughage may be up to 80% of the diet for recreation and leisure horses. Competition or sport horses, which often require greater digestible energy are thus provided both roughage and concentrate in a ratio (on a dry matter basis) of between 2 and 2.1: 1 [39,84]. The forage offered to these horses is frequently high-quality forage containing fermentable carbohydrates and a low level of neutral detergent fiber, resulting in high digestibility and short transit time. Forages with high digestibility are associated with reduced production of CH4, CO2, and H2 emissions, in part due to changes in the fermentative pathways [2].

The carbohydrate components of feed can include plant fibers that have been degraded anaerobically by microbiota with the release of CO2 and H2. Methanogens in the horse's hindgut use CO2 and H2 as critical components [2]. The dominant methanogens found in the horse microbiota are Methanobrevibacterium, which are also commonly found in the foregut of ruminants. This implies that horses may also produce CH4. However, acetogenesis rather than methanogenesis is the main CH4 sink in horses, and this may be a contributing factor to why horses emit less CH4 than other herbivores such as ruminants [88]. Within the literature it is reported that horses produce 3.3 times less CH4 (28 9 vs. 92 15 L/kg) than ruminants per unit of digested neutral detergent fiber [4].

Sustainability in relation to carbohydrates in the horse diet may not primarily focus on manipulations reducing methane production but rather avoiding using feedstuffs (grains) that compete with human food. From an efficiency of resources and ethical perspective it is difficult to justify the feeding of food grade grain or carbohydrates to livestock when over one billion people are on subsistence or below subsistence diets [89]. In the Nordic countries, and Sweden in particular, there has been a focus on demonstrating the ability to meet the DE requirements of sport and racehorses from highly digestible forage-based diets. These studies may provide a mechanism for a change in horse feeding practice that addresses sustainability needs and horse health [90,91].

5.2. The Role of Proteins

According to the NRC guidelines, horses require 1.26 g crude protein per kg bodyweight per day [92]. However, as protein synthesis and breakdown are energy expensive processes and the ability of the horse to utilize the crude protein on offer is dependent on energy balance [93]. It is therefore important to not consider protein intake and the potential for protein intake in isolation of the DE provided, as restricted energy supply results in greater protein catabolism and potential N loss in faces and urine. In most cases, given the literature reporting a high level of obesity in recreation horses the daily DE on offer should not limit the utilization of the crude protein on offer.

Roughage should provide the bulk of the equine diet and for intensively managed horses the substitution of lucerne (alfalfa) hay with temperate climate grass hay as a roughage source provides a mechanism to reduce some of the protein content of the ration. In some temperate climate countries, such as New Zealand, grass and grass hay have a relatively high crude protein content (up to 22%) and for horses in heavy work the addition of concentrates to the ration reduces the protein content of the diet and potential for N leaching [94]. Thus, these findings reflect the need for country or region-specific approaches to reducing the crude protein content of equine diets.

As most common feedstuffs offered to horses contain protein quantities that are sufficient, or even exceed (reportedly by 165%) the crude protein requirements for horses [51], the quality of the protein offered (amino acid distribution) is often more important than the quantity [95]. Theoretically the closer the amino acid profile matches the needs of the horse, the better the horse can utilize the protein provided, and thus less nitrogen (N) is excreted. However, further refinement of this concept is limited, in part due to the limited data published on the specific amino acid requirements of horses [96].

Soybean has been reported to generate less N in feces than other sources of protein used in horse feeds [67]. However, there are concerns that expansion of soybean production in some parts of the world are associated with deforestation, biodiversity loss, soil erosion and water contamination and rising carbon emissions. During the last 50 years, soy production has increased from 27 million tons to 269 million tons, causing environmental degradation of forests and savannas [97]. These negative side effects may negate the marginal returns achieved by increasing soybean as the source of dietary protein in the equine diet.

5.3. The Role of Fats

Oils are commonly used in feed as dietary additives due to their high small intestinal digestibility, and high energy density. In recent years, dietary oils have been used to both boost the energy content and reduce the relative starch content of the ration [21,98]. The use of oils potentially reduces fermentation through a direct substitution effect, replacing grain with the digestible oil, reducing the quantities of undigested grain reaching the hindgut and indirectly by manipulating the fermentative environment [88]. It has been reported that feeding a aa high level of oil (4.8% of total diet) could reduce fecal methane production by 9.2% [88]. Oil supplementation appears to reduce methane production by altering the acetate-to-propionate ratio and the saturation of unsaturated fatty acids to saturated fatty acids, reduces the hydrogen available for methanogenesis and inhibiting certain gut microbes such as bacteria, methanogens, and protozoa [3,99]. Each type of oil has a distinct fatty acid profile that is unique to that product. The bioactive compound in their fatty acid chain [100], particularly the medium-chain fatty acid [86], influences CH4 reduction [101]. Soya bean oil and corn oil are two dietary oils that have been shown to reduce CH4 in ruminants [102], which may be attributed to the reduction of unsaturated fatty acids and protozoa (which reduced hydrogen exchange with methanogens).

Although *in vivo* data for horses appears to be limited, current *in vitro* studies indicate that oil supplementation for horses with commonly used oils in equine feedstuffs may be a feasible mechanism to reduce CH4 production [88]. The challenge with substituting oils for concentrates in the diet is palatability, as well as the upper digestive threshold, which for a typical 500 kg horse is 100 mL to 150 mL per day. The high energy density of oils presents a limitation for use with most of the recreation / pet horses as these are often thrifty phenotypes and require a reduction in the energy density of the ration rather than an increase in energy density.

5.4. The Role of Vitamins and Minerals

Mineral supplements are frequently given to horses in amounts that exceed their requirements. The most common supplements offered horses are vitamin and mineral mixes, and even in the nonracing or sporting sector the level of supplementation is reported to be ∼65% of all horses [80,103]. The percentage of the horse population receiving supplements increases with the sporting and racing industries with up to 95% of racehorses in one survey receiving vitamin and mineral supplements, 90% an electrolyte supplement, and 60% a vitamin B or C supplement on a daily basis [104]. In sporting horses there was also a high level of supplementation with chondroprotectives, possibly reflecting the different age profile [71].

Excess provision of supplements will result in excretion in feces and urine and the resulting mineral leaching may have a negative environmental impact. In relation to nutrient management and leaching much attention is focused on N, P, and K but trace minerals, particularly Co, Cu, Mn, and Zn, should also be considered, as in high enough concentrations of trace minerals can be toxic to plants, microorganisms, and aquatic organisms [105,106].There is experimental data to demonstrate that not just the quantity of trace mineral provided, but the form of the trace mineral supplement can influence the leaching potential from compositing horse manure. Inorganic forms of trace mineral appear to have less digestibility than organic forms and result in higher concentration of trace mineral in manure compost [107]. However, there are limited data published to permit estimates of the relative quantities excreted at a horse level, or farm level, and thus the potential environment impact.

5.5. The Role of Other Feed Supplements

5.5.1. Digestive Tract Enhancers

Improved forage digestibility is one of the most highly recommended nutritional practices for reducing GHG emissions in both ruminants and nonruminants. However, to date despite much research there has been no single simple solution to manipulate the microbiota and improve forage digestibility. In vitro studies have indicated that *Saccharomyces cerevisiae* supplementation may provide a potential mechanism to reduce methane production via its ability to induce acetogen growth [24] which subsequently competes with methanogens for H2 [108]. However, to date there does not appear to be published literature demonstrating the *in vivo* effect within horses.

5.5.2. Plant Extracts

Handlers, owners, and trainers of equines routinely use herbs for a variety of purposes, such as therapeutic or feed additives [71,79,87,101]. Plant extracts are believed to provide a range of benefits, including im0proved performance, increased daily weight gain and more recently reduced CH4 emissions. Elghandour et al. [109] found that a *Salix babylonica* extract, which is common in Mexico reduced CH4 output in 24 and 48 hours *in vitro* incubations compared to the control incubations. However, to date, we do not have *in vivo* data to demonstrate the feasibility of this plant extract, or other plant extracts, to reduce CH4 production in horses.

6. Conclusion

As a monogastric hindgut fermenter the horses emits less CH4 per kg bodyweight than a ruminant. The horse is also more efficient at protein digestion, and thus could have lower N excretion per kg bodyweight than ruminants. However, these relative advantages compared to ruminants does not mean that CH4 production and N leaching should not be considered within the equine industry. Increasing numbers of horses and intensive management provide challenges in meeting sustainability goals. Strategic modifications to horse feeding focusing on highly digestible forages, processed grain rather than raw grains, avoiding overfeeding and over supplementation could moderate the environmental impact of increasing numbers of intensively managed equids in Western Europe. As a predominately nonproduction animal there may be an ability within the equine industry to tolerate small increases in feed prices to permit strategies to mitigate feed production processes that are antagonistic to sustainability goals.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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