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Effects of forage feeding to calves on performance, rumen fermentation, and nutrient digestibility: A meta-analysis

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ABSTRACT

The literature on whether or not to feed forage is marked by inconsistencies, largely due to various factors associated with forage inclusion in calf diets. To elucidate these factors, we conducted a 3-level meta-analysis to comprehensively investigate the overall effects of forage provision in young calves. We searched for studies published between 2000 and 2023 in Google Scholar, ScienceDirect, and X-Mol. Moderator analyses were performed to evaluate the effects of different forage sources, forage provision methods, starter forms, milk levels, and forage levels on the heterogeneity of growth performance, rumen fermentation, and nutrient digestibility outcomes in studies feeding forage to calves. A mixed-effect model was used to predict the relationship between forage level and performance. Funnel plots and Egger's test were used to determine publication bias. A total of 86 treatment comparisons from 36 articles were included in the final dataset. The weighted mean difference was used to evaluate the effect size, and the statistical heterogeneity of the effect size was estimated using Cochrane's Q test. The results showed that forage supplementation improved growth performance, structural growth, and development of rumen fermentation in calves. However, moderator analyses revealed that several factors, including forage source, feeding method, physical form of starter, milk feeding level, and forage feeding level might contribute considerably to variability, resulting in significant heterogeneity in the effects of forage provision in calves. Larger effect sizes were found for oat hay (OH) supplementation rather than alfalfa hay (AH) or straw, and for feeding forage as a free choice (FC) compared with a TMR (defined as a mixture of calf starter and forage), especially when forage was fed as a FC resulting in higher total DMI and body barrel. Forage supplementation was more effective in boosting calf growth in calves provided with ground starter than in calves fed pelleted and textured starter. Greater effects were shown for AH supplementation than OH or straw in improving rumen fermentation parameters. Furthermore, compared with the preweaning period, the effect of providing forage on calves was more noticeable in the postweaning period. The results of the mixed-effects model analysis indicated that calves can be efficiently fed 12% of DM as forage during the preweaning period to support their growth and development. Meanwhile, 9% of DM might be the optimal level for feeding OH and straw to preweaning calves. More studies are essential to explore how different levels of AH dietary supplementation affects calves during the preweaning period and improve the consistency and accuracy of the dose-response curve predictions. Overall, growth performance and rumen fermentation of dairy calves were affected by forage inclusion. Moreover, forage source, feeding method, physical form of starter, milk feeding level, and forage level are essential factors that result in different degrees of effect on the calf's performance and rumen fermentation.

Key words: forage, dairy calves, growth performance, meta-analysis

INTRODUCTION

The debate on whether calves should be fed forage has received considerable attention in recent years, though research in this area has occurred since the mid-20th century (Pounden et al., 1951; Hibbs et al., 1956; Phillips, 2004; Movahedi et al., 2017). However, previous studies on the effects of forage on calf growth performance have yielded inconsistent results (Xiao et al., 2021a), leading to a lack of uniform recommendations in practical applications. Studies in the United States showed that operations feeding some form of forage before weaning had declined in the recent past from 86.7% to 43.3% in a span of 20 years, an indication of changes in preferences among dairy producers (Heinrichs et al., 1994; Urie et al., 2018). Proponents report that forage supplementation is beneficial to calves, as it enhances growth as a result of improved feed intake and efficiency (Coverdale

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et al., 2004). Furthermore, it has been argued that giving calves forage could modulate the rumen environment, as reflected in time spent ruminating (Omidi-Mirzaei et al., 2018), improvement of the rumen's macroscopic appearance (Suárez et al., 2007), and enhancement of the rumen's muscular growth (Beiranvand et al., 2014). Greater rumination plays a major role in increasing ruminal fluid pH (Daneshvar et al., 2015; Lin et al., 2018; Xiao et al., 2021a), mitigating ruminal acidosis and thus augmenting gut health in the growing calves. On the other hand, those against forage feeding counter with the thesis that calves have an underdeveloped rumen epithelium (Schwartzkopf-Genswein et al., 2003) and hence cannot effectively utilize forage during the milk feeding stage due to a limited rumen capacity (Hill et al., 2008). Rather, they suggest calves should be fed concentrates which encourage the production of butyrate and propionate, which are critical for rumen development in the preweaning period (Hibbs et al., 1956). However, concentrates are highly palatable and digestible, and their feeding might result in abundant production of VFA based on the rapidly fermented carbohydrate (Suárez et al., 2006) and could aggravate ruminal acidosis in calves by impairing rumination and salivation and subsequently digestibility of nutrients in the rumen (Khan et al., 2016).

Calves require a sufficient supply of energy and proteins to support growth and attain the recommended BW by the time they are weaned. A mature gut improves feed digestibility, resulting in more nutrients to support metabolism and calf growth. Concentrates readily supply the nutrients to support the rumen growth and development. However, feeding forage can interfere with DM digestibility (**DMD**) and OM digestibility (**OMD**) in dairy calves (Leibholz, 1975; Hill et al., 2019). Compared with calves fed no forage, the total-tract apparent DMD, OMD, and CP digestibility (**CPD**) values were lower in calves fed forage (Daneshvar et al., 2015). However, the CPD in calves fed alfalfa hay (**AH**) was greater compared with those fed starter without forage, but similar to those fed wheat straw and beet pulp (Movahedi et al., 2017). Furthermore, several investigators have noted that no detectable differences were observed in DMD, OMD, or CPD when calves were fed either AH in addition to concentrate or concentrate only (Hosseini et al., 2016; Maktabi et al., 2016). Many factors have been linked to the confounding results, including forage source, forage levels, physical form of starter (Ghaffari and Kertz, 2021), forage feeding methods, and milk feeding strategy (Imani et al., 2017). Moreover, several studies have indicated that feeding a higher milk plane could further improve the performance of dairy calves fed forages (Gelsinger et al., 2016; Bahmanpour et al., 2023). Recently, some studies in young calves have found that feeding a TMR is a more ideal choice than a free choice diet (**FC**; feeding starter and forage in different buckets; Gasiorek et al., 2020). Provision of NDF from AH in addition to the calf starter diet was more effective than providing beet pulp in improving rumen pH and chewing activity, without concomitant effects on starter intake or ADG (Maktabi et al., 2016).

Although the issue of forage feeding in growing calves has been explored using meta-analytical tools (Imani et al., 2017), consensus on whether or not calves should be fed forage has remained elusive (NASEM, 2021). Similarly, despite increased research output in this area, the findings are inconsistent and context-dependent. Additionally, the ideal forage level is not known, with studies utilizing different types of forages. Experiments have used forages such as bromegrass hay (Coverdale et al., 2004), oat hay (**OH**; Gasiorek et al., 2020), and AH (Beiranvand et al., 2014). Moreover, comparisons between different forage types are limited in the literature (Antúnez-Tort et al., 2023), although differences in the impact of feeding forage on calf performance might exist. Meanwhile, because of the hierarchical structure of research, the conventional meta-analytical methods are prone to inaccuracies (Hedges et al., 2010). Therefore, the objectives of this study were (1) to evaluate the effect of forage provision to calves on growth performance, structural growth, rumen fermentation, and nutrient digestibility; (2) to determine the roles that forage sources, method of forage provision, physical form of starter, and milk feeding level play in the heterogeneity of responses to forage feeding; and (3) to determine the optimal level of forage provision to improve growth performance based on the data in the articles reporting on the forage level.

MATERIALS AND METHODS

Study Search and Eligibility Criteria

We searched for studies published between 2000 and 2023 in Google Scholar (https://scholar.google.com/), ScienceDirect (https://www.sciencedirect.com/), and X-Mol (https://www.x-mol.com/) databases. The principal search words were "calves," "forage," "performance," "rumen," and "digestibility." Following the participant, intervention, comparison, outcome, and study design (PICOS) principle (Liberati et al., 2009), we read the title and abstract of the articles to decide which studies could be included. We excluded reviews, literature of investigation, articles with experiments designed using Latin square, literature with animals other than calves, and literature containing no randomized controlled trials. Trials must have included a control group that did not feed any forage or hay and one or more intervention groups that at least feed one type of forage or hay. Furthermore, some essential data had to be presented, such as the number of experimental animals, mean, SE or SD, and consistent weaning age. In total, according to the inclusion criteria, a total of 36 articles (39 studies) with 86 comparisons were included in the meta-analysis (White et al., 2016; Lean et al., 2019).

Risk of Bias in Studies Included

The Systematic Review Centre for Laboratory Animal Experimentation bias risk tool was used to evaluate the risk of bias (Hooijmans et al., 2014). The items considered were as follows: (1) selection bias: random sequence generation, allocation concealment, baseline characteristics; (2) performance bias: blinding participants and personnel, random animal housing; (3) detection bias: random outcome assessment, blinding outcome assessors; (4) attrition bias: incomplete outcome data; (5) reporting bias: selective outcome reporting; (6) other bias: other sources of bias. Studies were classified as having a high, low, or unknown risk of bias for each item.

Data Extraction

The information included in the studies used in the final data set included basic information on the publications (first author, year of publication), treatments (number of samples in each group), calves (initial BW, weaning age, duration of the experiment), forage source, forage feeding method, physical form of starter, and milk feeding level, which was calculated using the average daily milk level in L/d over the milk feeding phase, adjusted for 12.5% DM.

The following data were selected and used in this meta-analysis:

(1) Growth performance: total DMI (**TDMI**), starter intake, BW, ADG, and feed efficiency (**FE**).
(2) Structural growth: body barrel, body length, heart girth, withers height, and hip height.
(3) Ruminal fermentation parameters: total VFA (**TVFA**), acetate, propionate, butyrate, and acetate/propionate ratio (**A:P**).
(4) Nutrient digestibility: DMD, OMD, neutral detergent fiber digestibility (**NDFD**), and CPD.

Because units in different articles differed for some parameters, we unified the units where possible. For example, the unified unit of starter intake was kg/d.

If the SD of the mean was not reported in the article, we calculated it using the formula conversion for SE into SD: $SD = SE \times \sqrt{n}$.

Statistical Analysis

Due to similarity in the units of extracted data, the weighted mean difference (**WMD**) between the treatment group given forage, and the control group without forage was used to assess the effect of forage provision on dairy calves. In R software (version 4.3.2; http://www.r-project.org) using the "escalc" function in the "metafor" package, we calculated WMD and its variance for each treatment comparison in all continuous variables. Coefficients and CI may be inflated by type I error if the number of included studies is small or moderate (Tipton, 2015). Thus, in our meta-analysis, we used the small-sample adjustment function. When multiple studies yield estimates based on the same subjects or when non-independent studies (e.g., conducted by the same researcher or laboratory) are grouped together, the independence assumption is broken (Hedges et al., 2010). In this study, the data had a hierarchical structure because comparisons were nested within experiments, i.e., 86 comparisons from 36 articles. Thus, the total effect sizes were computed using a 3-level random meta-analytic model (Van den Noortgate et al., 2013; Assink and Wibbelink, 2016), which accounted for various sources of dependence within and across studies, being superior to the fixed-effects approaches used in traditional meta-analyses. Three sources of variance were modeled: the sampling variance for each effect size (level 1), the variance between effect sizes within studies (level 2), and the variance across studies (level 3). We ran 2 independent log-likelihood-ratio tests to determine if the within-study variation and between-study variance were significant. Within-study variance arises from individual differences across samples within the same study, as well as factors such as measurement error. Between-study variance indicates the variability of effect sizes across studies, which may be caused by factors such as differences in study design, sample characteristics, interventions, and measurement tools. If the level 2 and level 3 variances were significant, then we concluded that there was heterogeneity of effect sizes. Meanwhile, the heterogeneity was also examined by calculating the distribution of the variance over the 3 levels of the meta-analytic model. A moderator analysis was carried out if the sampling variance was smaller than 75% based on the 75% rule (Hunter and Schmidt, 2004), indicating a significant variation between effect sizes within studies or between studies.

When 8 or more separate studies were available and the overall effect of the independent variable was significant and with high heterogeneity, a moderator analysis was conducted (Tanner-Smith and Tipton, 2014). With WMD as the dependent variable, meta-regression analysis was used to determine the impact of the covariates (forage source, forage offering method, starter form, milk feeding level and forage feeding level) in calves.

Forest plots represent a very simple and intuitive description of the statistical results and were the most commonly used expression of results in this meta-analysis. We chose the random effects model to finish the forest plots, as an element of randomness is inevitable when pooling data from individual studies.

Publication bias has the potential to undermine the validity and precision of a meta-analysis's findings. Thus, one study with statistically significant findings has a higher chance of being published than studies with null or nonsignificant findings (Piray and Foroutanifar, 2022). When more than 10 separate studies were included, a visual inspection of funnel plots and Egger's test were used to determine publication bias. The funnel plot was visually examined to determine whether there was bias from a subjective point of view by observing the symmetry of the funnel plot. The Egger's test was applied, as it further quantitatively assesses the symmetry of the funnel plot. If the Egger's P-value was <0.05, it indicated publication bias.

Microsoft Excel (Microsoft Corp., Redmond, WA) was used to capture all the data in the study, which were later exported into R software (version 4.3.2; http://www.r-project.org) with the "metafor" packages for statistical analyses and plots.

A mixed-effects model (St-Pierre, 2001) was used to predict the optimal forage level in relation to performance. This made it possible to analyze the fixed impact of independent variables as well as the effect of study, which was considered a random factor. The general single model is shown as follows:

$$Y_{ij} = B_0 + B_1X_{ij} + B_2X^2_{ij} + s_i + b_iX_{ij} + e_{ij},$$

where Y_{ij} is the dependent variable (ith study 1, ...m, jth observation 1, ...ni), B_0 is the overall intercept across all studies, B_1 is the coefficients of explanatory variables, B_2 is the quadratic coefficient of explanatory variables, X_{ij} is the value of the predictor variable (forage level), s_i is the random effect of study i, b_i is the random slope associated with the ith study, and e_{ij} is the unexplained residual error. Both R and StataIC 15 were used to investigate the mixed regression analysis, and the results were the consistent. However, to improve the visualization of the data, graphing was done using the R programming language.

RESULTS

The screening flowchart of literature and the overall risk of bias across studies for various domains are as shown in Figure 1. None of the studies met all the 10 requirements for low risk of bias. In a majority of the studies, inadequate reporting led to a high bias risk. Considering selection bias, none of the studies accurately described the random sequence generation and allocation concealment. Most studies appeared to be comparable for the baseline characteristics. The random animal housing and the blinding of participants and personnel reflected a performance bias, whereby authors did not report the measures taken to reduce bias. Similarly, it was not completely evident from the articles included in the meta-analysis which measures were used to reduce detection bias: i.e., not describing all of the measures that were used to blind outcome assessor from knowing which intervention each animal received (item 6) and failure to describe which methods were used to randomly select animals for outcome assessment (item 7). A majority of the studies had a low risk of bias with regard to the incomplete outcome data (attrition bias risk). Moreover, neither selective outcome reporting bias nor additional sources of bias were identified.

The basic information of the 36 studies used in the study is listed in Table 1, including the author, years of publication, forage source, forage level, and forage offering method. The forage sources used were diverse and included AH, straw (wheat, barley), OH, and others (beet pulp, ryegrass hay, grass hay, coastal Bermudagrass, timothy hay, and orchard hay). Meanwhile, the methods of forage feeding were also presented, which included as a TMR and FC.

Using funnel plots and Egger's tests (Supplemental Figure S1, see Notes), ADG and starter intake in the preweaning period; weaning hip height, TVFA, and propionate concentration in the postweaning period; and butyrate concentration presented a publication bias (P < 0.05).

Effect of Forage Provision on Feed Intake and Growth Performance

Table 2 provides the overall effect of forage provision on TDMI, starter intake, ADG, FE, and BW in dairy calves. The TDMI increased with forage supplementation in calves during the preweaning (WMD = 0.07 kg/d, [0.03, 0.10], P < 0.01), postweaning (WMD = 0.24 kg/d, [0.07, 0.41], P = 0.01), and overall (WMD = 0.10 kg/d, [0.02, 0.17], P = 0.01) periods. Thus, TDMI was selected as the primary indicator of performance to investigate the relationship between forage level and growth performance. Using moderator analyses, we determined that forage feeding level had a significant impact on the preweaning TDMI in calves given forage (P = 0.05). Moreover, increased starter intake was evident in calves

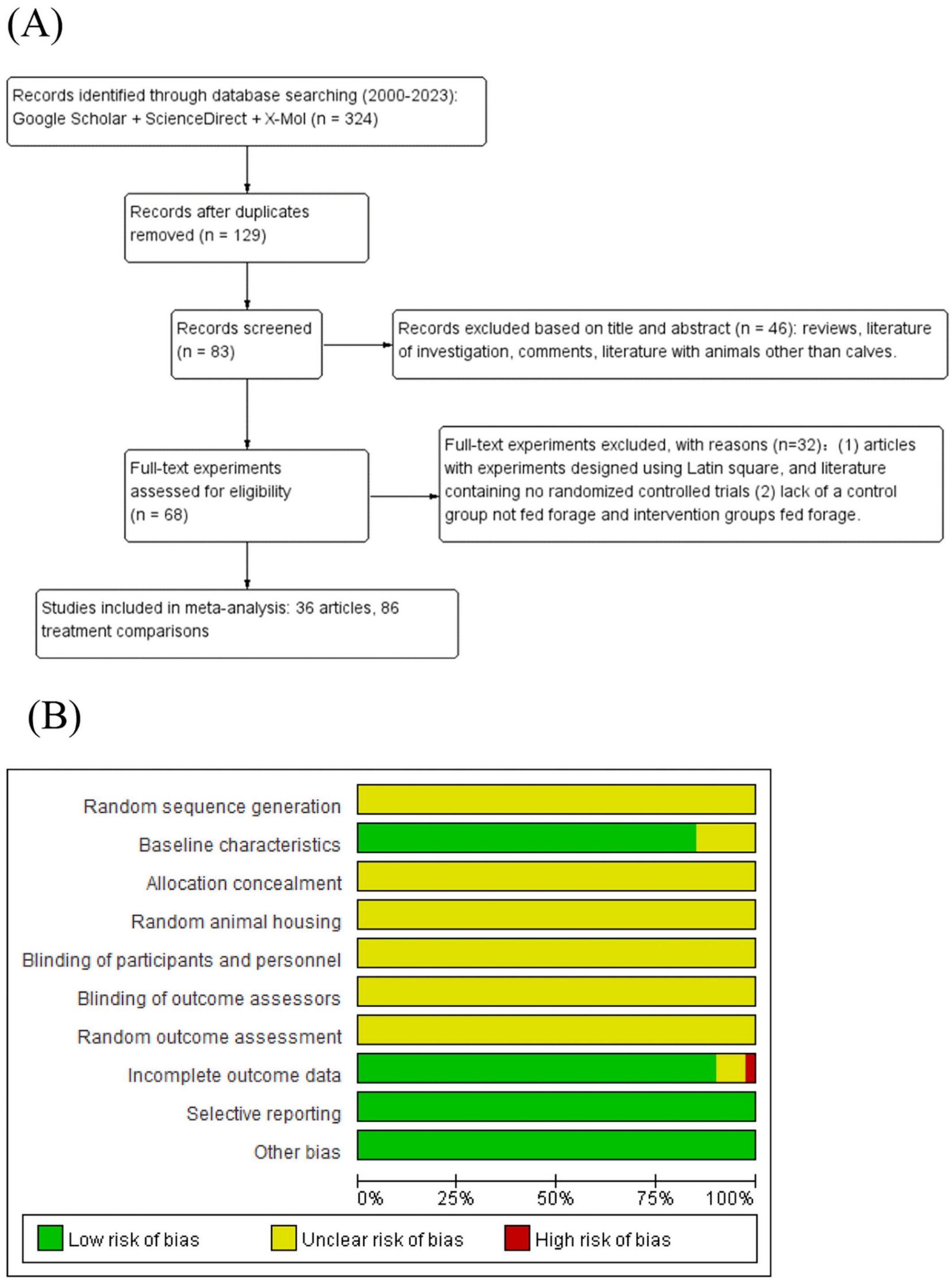

Figure 1. (A) The Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) flow diagram. (B) The Systematic Review Centre for Laboratory Animal Experimentation (SYRCLE) bias risk, indicating the proportion of studies with low, unclear, or high risk of bias.

fed forage during the preweaning (WMD = 0.03 kg/d, [0.01, 0.07], P = 0.03) and postweaning (WMD = 0.12 kg/d, [0.01, 0.23], P = 0.04) periods, whereas a tendency toward increase (WMD = 0.05 kg/d, [−0.01, 0.12], P = 0.09) was observed in the overall period. Compared with the control group, forage supplementation significantly increased (WMD = 0.03 kg/d, [0.01, 0.04], $P < 0.01$) and tended to increase ADG (WMD = 0.05 kg/d, [0.00, 0.09], P = 0.07) in the preweaning period and postweaning periods. Though forage provision showed no effects on FE

Table 1. Summary of the published studies included in the meta-analysis on of effects of forage provision on performance dairy calves[1]

Reference	Trt	Calf/trt	Initial BW[2] (kg)	Start of forage feeding[2] (d)	Weaning age	End of experiment (d)	Forage source	Forage level (%)	Milk level (L/d)	Cutting length/processing	Starter form	Forage offering method
Bagheri et al., 2021	4	12	43.8 ± 3.2	15	56	90	Wheat straw	Ad libitum	5	Chopped <19 mm	Ground	FC
Bahmanpour et al., 2023	4	8	36.43 ± 2.1	3	56	70	Alfalfa	0, 15	3.8, 7.3	Chopped	Finely ground	TMR
Castells et al., 2013	3	5	43.7 ± 4.39	8	57	78	Alfalfa hay, oat hay	—	3.7	Chopped	Pelleted	TMR
Castells et al., 2012 (1)	3	20	43.8 ± 5.7	14	57	71	Alfalfa hay, ryegrass hay	—	3.7	Chopped	Pelleted	FC
Castells et al., 2012 (2)	3	20	46.1 ± 5.0	14	57	71	Oat hay, barley straw	—	3.7	Chopped	Pelleted	FC
Castells et al., 2015	2	30	39.5 ± 3.76	6.7 ± 2.12	52	65	Oat hay	0, 12	4.1	Chopped	Ground	TMR
Coverdale et al., 2004	4	14	44.2 ± 5.0	2–5	31	64	Grass hay	0, 7.5, 15	4	Chopped 8 to 19 mm	Coarse, ground	TMR
Daneshvar et al., 2015	4	10	41.2 ± 3	3	60	74	Alfalfa hay	0, 15	5, 5.1	Chopped	Finely ground	TMR
EbnAli et al., 2016	3	15	41.2	3	56	70	Alfalfa hay	0, 10	4.4	GMPL 3 mm	Finely ground	TMR, FC
Gasiorek et al., 2020	4	10	39.6 ± 0.39	3	56	84	Oat hay	0, 10	6.5	Chopped 2 ± 0.5 cm	Pelleted	TMR, FC
Gasiorek et al., 2022	4	11	39.6 ± 0.39	3	56	84	Triticale straw	0, 10, 15, 20	6.5	Chopped 2 ± 0.5 cm	Pelleted	TMR
Hill et al., 2008 (3)	3	16	42 ± 1	3–5	31–32	28	Timothy	0, 2.5, 5	5.1	GMPL 2.2 mm	Textured	TMR
Hill et al., 2019	2	24	45.4 ± 1.18	2–3	42	56	Long timothy hay	—	4.2	20 to 40 cm	Ground	FC
Hill et al., 2010 (1)	4	12	—	2–4	28	56	Wheat straw	0, 3, 6, 9	5.5	GMPL 2.8 mm	Textured	TMR
Hill et al., 2010 (2)	4	12	—	2–4	28	56	Alfalfa hay	0, 5, 10, 15	5.5	Chopped to 1.7 mm	Textured	TMR
Hill et al., 2010 (3)	4	12	—	2–4	28	56	Grass hay	0, 3, 6, 9	5.5	GMPL 1.7 mm	Textured	TMR
Horvath et al., 2019	2	16	45.4 ± 1.18	17 ± 3	56	56	Coastal Bermudagrass	0, 20	7.9	Chopped to 5 cm	Pelleted	FC
Hosseini et al., 2019	6	10	41 ± 3.6	4	56	70	Wheat straw	0, 7.5, 15	3.7, 6.1	GMPL 7.9 mm	Ground	TMR
Hosseini et al., 2016	4	10	40.5 ± 4	14, 28, 42	57	73	Alfalfa hay	0, 15	4	GMPL 3 mm	Ground	TMR
Iqbal et al., 2019	3	10	27.25 ± 0.95	4 ± 1	—	84	Oat hay	0, 15	5.5	Chopped to 1.5 cm vs. pellet size 4 × 18 mm	Pelleted	TMR
Jahani-Moghadam et al., 2015	3	11	38.8 ± 1.1	3	76	90	Alfalfa hay	0, 10	6.7	GMPL 5.4 mm vs. 5.8 mm	Semi-textured	TMR
Khan et al., 2011	2	15	—	3	56	70	Orchard grass hay	Ad libitum	6	Chopped 1.2 ± 0.4 cm	Textured	FC
Kim et al., 2016	2	8	73.5 ± 4.2	28	56	77	Timothy hay, orchard hay	0, 20	1.8	—	—	TMR
Lin et al., 2018	3	6	42 ± 3	14, 42	63	63	Oat hay	—	4	—	—	FC
Maktabi et al., 2016	4	13	41.7 ± 3.3	4	50	70	Alfalfa hay, beet pulp	0, 10, 20	4.7	~1 mm	—	TMR
Mirzaei et al., 2015	5	10	42.7 ± 2.2	16	51	72	Alfalfa hay	0, 8, 16	3.9	GMPL 2.92 vs. 5.04 mm	Ground	TMR
Mirzaei et al., 2016	6	10	42.2 ± 2.5	3	49	63	Alfalfa hay	15	3.6	Chopped <18 mm	Finely ground	TMR
Movahedi et al., 2017	4	10	41.2 ± 3.5	4	—	80	Alfalfa hay, wheat straw, beet pulp	Ad libitum	3.9	Chopped to 1.18–18 mm	Ground	FC
Nemati et al., 2016	3	15	41 ± 2.5	3	51	70	Alfalfa hay	0, 12.5, 25	3.8	GMPL 3 mm	Finely ground	TMR
Overvest et al., 2015	4	12	—	1	50	84	Grass hay	0, 15	12.8	Chopped <2.5 cm	Textured	TMR, FC
Suárez et al., 2007	8	8	46 ± 3.0	10	70	70	Barely straw, grass	0, 30	6.1	Chopped	Pelleted	TMR
Terré et al., 2015 (2)	3	20	40 ± 4.6	8	52	58	Ryegrass straw	—	4.5	Chopped <19 mm	Pelleted, textured	FC
Terré et al., 2013	4	16	43.4 ± 4.51	9	52	64	Oat hay	Ad libitum	4.3	Chopped	Pelleted	FC
Türkmen et al., 2023	3	7	46.69 ± 4.14	3	56	56	Alfalfa hay, grass hay	Ad libitum	5.2	Chopped	Pelleted	FC
Wu et al., 2018	5	8	40.6 ± 5.8	3, 15	56	56	Oat hay, alfalfa hay	—	6.5	Chopped	Textured	FC
Xiao et al., 2018	3	10	38.2 ± 2.1	2	56	70	Mixed hay (AH, OH)	Ad libitum	6.7	Chopped <2.5 cm	Pelleted	FC

Continued

Table 1 (Continued). Summary of the published studies included in the meta-analysis on of effects of forage provision on performance dairy calves[1]

Reference	Trt	Calf/trt	Initial BW[2] (kg)	Start of forage feeding[2] (d)	Weaning age	End of experiment (d)	Forage source	Forage level (%)	Milk level (L/d)	Cutting length/processing	Starter form	Forage offering method
Xiao et al., 2021a	3	70	35.72 ± 0.29	14	56	70	Oat hay	—	6.8	10–12 vs. 3–5 cm	Pelleted	FC
Xiao et al., 2021b	2	20	38.5 ± 2.4	1	56	70 (196)[3]	Mixed hay (AH, OH)	Ad libitum	6.7	Chopped	Pelleted	FC
Xiao et al., 2023a	4	21, 26, 21, 16	41.5 ± 4.2	5.1 ± 0.8, 7.9 ± 0.8, 12.1 ± 1.4	56	84 (196)[3]	Oat hay	Ad libitum	8.3	Chopped <2.5 cm	Pelleted	FC

[1]Trt = treatment; FC = free choice; GMPL = geometrical means particle length;

[2]Values are presented as mean ± SD.

[3](196) refers to the end time of the long-term observation of the calves after the main experiment was terminated.

during the preweaning ($P = 0.92$) and postweaning ($P = 0.16$) periods, it tended to decrease FE (WMD = 0.01, [−0.02, 0.00], $P = 0.08$) overall. Supplementation with forage increased weaning (WMD = 1.50 kg, [0.99, 2.00], $P < 0.01$) and final (WMD = 2.36 kg [1.26, 4.00], $P < 0.01$) BW.

A significant level of heterogeneity was observed for pooled TDMI during the preweaning (percentage of variance explained [**%Var.**] level 1 = 34.2%), postweaning (%Var. level 1 = 22.1%) and overall (%Var. level 1 = 18.6%) periods, starter intake during the preweaning (%Var. level 1 = 21.3%), postweaning (%Var. level 1 = 15.6%) and overall (%Var. level 1 = 25.2%) periods, and final BW (%Var. level 1 = 47.9%). The results of the likelihood ratio test showed a considerable variance at both the within-study (level 2) and between-study (level 3) levels. We hypothesized that the forage source, feeding method of forage, starter forms, and milk feeding level caused the aforementioned observations in heterogeneity. In addition, the number of studies used to obtain the results were more than 8. Hence, a moderator analysis was conducted to test our hypothesis.

The moderator analysis (Table 3) showed that AH (WMD = 0.07 kg/d, [0.02, 0.12], $P = 0.01$), OH (WMD = 0.11 kg/d, [0.04, 0.17], $P < 0.01$), and straw (WMD = 0.06 kg/d, [−0.02, 0.15], $P < 0.01$) supplementation had a significant effect on TDMI during the preweaning period. The OH provision tended to increase TDMI during the postweaning (WMD = 0.28 kg/d, [0.01, 0.57], $P = 0.06$) and overall (WMD = 0.14 kg/d, [−0.27 0.12], $P = 0.08$) periods. Providing forage as an FC (WMD = 0.09 kg/d, [0.04, 0.14], $P < 0.01$) and TMR (WMD = 0.06 kg/d, [0.01, 0.10], $P = 0.02$) could increase preweaning TDMI. Moreover, calves fed forage as a FC (WMD = 0.30 kg/d, [0.06, 0.54], $P = 0.02$) and TMR (WMD = 0.22 kg/d, [0.03, 0.40], $P = 0.03$) had greater TDMI compared with calves without forage during the postweaning period. The moderator tests showed that both the starter form ($P = 0.02$) and the milk feeding level ($P = 0.02$) influenced the effects of forage provision on TDMI. Forage increased TDMI in calves fed ground starter intake during the preweaning (WMD = 0.09 kg/d, [0.06, 0.13], $P < 0.01$), postweaning (WMD = 0.57 kg/d, [0.33, 0.80], $P < 0.01$), and overall (WMD = 0.20 kg/d, [0.08, 0.31], $P < 0.01$) periods. Similarly, calves fed milk at both ≤4 and >4 to ≤6 L/d showed an increase in TDMI by forage provision during the preweaning, postweaning, and overall periods ($P \leq 0.05$).

Supplementation with OH (WMD = 0.06 kg/d, [0.01, 0.12], $P = 0.03$) increased preweaning starter intake compared with the control diet without forage (Supplemental Table S1, see Notes). Feeding forage as a FC increased starter intake during the preweaning (WMD = 0.06 kg/d, [0.02, 0.11], $P < 0.01$) period. When calves were fed

Table 2. The effect size estimates of forage on intake and growth performance in dairy calves[1]

Item	$s(k)$	WMD [95% CI]		Variance component		%Var. level 1	%Var. level 2	%Var. level 3
		Effect size	*P*-value	σ^2_{level2} (*P*-value)	σ^2_{level3} (*P*-value)			
TDMI (kg/d)								
Preweaning	22 (48)	0.07 [0.03, 0.10]	<0.01	0.003 (<0.01)	0.003 (0.05)	34.2	32.2	33.6
Postweaning	13 (26)	0.24 [0.07 0.41]	0.01	0.013 (0.05)	0.058 (<0.01)	22.1	13.9	64.0
Overall	18 (46)	0.10 [0.02, 0.17]	0.01	0.002 (0.02)	0.017 (<0.01)	18.6	8.8	72.6
Starter intake (kg/d)								
Preweaning	23 (53)	0.03 [0.01, 0.07]	0.03	0.002 (<0.01)	0.002 (0.05)	21.3	36.5	42.2
Postweaning	16 (41)	0.12 [0.01, 0.23]	0.04	0.023 (<0.01)	0.027 (0.03)	15.6	39.0	45.4
Overall	16 (40)	0.05 [−0.01, 0.12]	0.09	0.005 (<0.01)	0.007 (0.03)	25.2	31.7	43.1
ADG (kg/d)								
Preweaning	29 (63)	0.03 [0.01, 0.04]	<0.01	0.000 (0.50)	0.000 (0.18)	77.9	0	22.1
Postweaning	24 (53)	0.05 [0.00, 0.09]	0.07	0.002 (<0.01)	0.009 (<0.01)	30.8	12.9	56.3
Overall	22 (55)	0.02 [−0.02, 0.06]	0.33	—	—	—	—	—
FE								
Preweaning	23 (54)	0.00 [−0.01, 0.01]	0.73	—	—	—	—	—
Postweaning	19 (46)	−0.01 [−0.02, 0.01]	0.16	—	—	—	—	—
Overall	22 (56)	−0.01 [−0.02, 0.00]	0.08	—	—	—	—	—
BW (kg)								
Weaning	22 (51)	1.50 [0.99, 2.00]	<0.01	0.047 (0.48)	0.000 (0.50)	98.6	1.4	0
Final	25 (59)	2.63 [1.26, 4.00]	<0.01	1.368 (0.17)	6.700 (<0.01)	47.9	8.8	43.3

[1]TDMI = total DMI; FE = feed efficiency expressed as kg of ADG divided by kg of TDMI ratio; s = number of studies; k = number of effect sizes; WMD = weighted mean differences between treatment group with forage supplementation and control group without forage, calculated using a robust regression hierarchical model to account for nesting of treatments within study; σ^2_{level2} = variance between effect sizes within the same study; σ^2_{level3} = variance between studies; %Var. level 1 indicates the degree to which within-individual differences contribute to the total variation; %Var. level 2 indicates the extent to which differences between treatments or conditions within the same study contribute to the total variation; %Var. level 3 indicates the proportion of total variation attributable to differences between studies.

ground starter, forage provision had a significant effect on starter intake during the postweaning (WMD = 0.21 kg/d, [0.03, 0.38], $P = 0.02$) and overall (WMD = 0.08 kg/d, [0.00, 0.17], $P = 0.05$) periods. Providing forage to calves fed ≤4 L/d of milk increased starter intake during the preweaning (WMD = 0.07 kg/d, [0.01, 0.12], $P = 0.01$), postweaning (WMD = 0.22 kg/d, [0.05, 0.40], $P = 0.02$) and overall (WMD = 0.09 kg/d, [0.01, 0.17], $P = 0.02$) periods.

During the postweaning period, calves fed OH ($P = 0.01$) using the FC method ($P = 0.04$), those fed ground starter ($P = 0.02$), and those fed ≤4 L/d of milk ($P = 0.03$) gained ADG (Supplemental Table S2, see Notes) due to forage supplementation. Moderator analyses showed a significant effect of OH supplementation (WMD = 5.88 kg/d, [3.12, 8.63], $P < 0.01$) in calf diets by increasing final BW compared with AH (WMD = 1.50 kg/d, [−0.57, 3.57], $P = 0.15$), straw (WMD = 2.33 kg/d, [−0.09, 4.74], $P = 0.06$), and other forages (WMD = 2.00 kg/d, [−0.22, 4.21], $P = 0.08$). Calves fed forage using the FC method (WMD = 3.75 kg/d, [1.97, 5.53], $P < 0.01$) and a TMR (WMD = 1.83 kg/d, [0.24, 3.41], $P = 0.03$) had a greater final BW. Providing forage to calves fed ground starter (WMD = 3.34 kg/d, [1.12, 5.56], $P < 0.01$) and pelleted starter (WMD = 3.11 kg/d, [0.97, 5.25], $P < 0.01$) increased final BW. Similarly, forage supplementation caused calves fed ≤4 L/d of milk ($P < 0.01$) and >4 to ≤6 L/d of milk ($P = 0.04$) to increase the final BW.

Effect of Forage Provision on Structural Growth of Calves

Table 4 provides the overall effect of forage provision on body barrel, body length, heart girth, withers height, and hip height in dairy calves. When calves were provided forage, body barrel (WMD = 2.24 cm, [0.08, 4.40], $P = 0.04$) and body length (WMD = 0.64 cm, [−0.01, 1.28], $P = 0.05$) increased during the postweaning period. Whether in the preweaning or postweaning period ($P > 0.27$), there were no significant differences in heart girth, withers height, and hip height in calves fed forage compared with those fed calf starter only. A significant heterogeneity was observed in body barrel (%Var. level 1 = 2.1%), and body length (%Var. level 1 = 66.6%) measurements during the postweaning period. Furthermore, more than 8 studies were used to get the outcomes, so moderator analyses were carried out (Supplemental Table S3, see Notes).

Feeding forage to calves as a TMR ($P = 0.07$) tended to increase final body barrel, and feeding ≤4 L/d milk increased body barrel of calves ($P < 0.01$). Both the forage source ($P < 0.01$) and the feeding method ($P < 0.01$) were found to influence the effects of feeding forage on final body length. The OH and straw provision and using FC method increased the final body length ($P < 0.01$). Compared with calves without forage, providing forage to calves fed ground starter (WMD = 2.61 cm, [0.76,

Table 3. The moderator analyses on TDMI in dairy calves[1]

Item	*s*(*k*)	WMD [95% CI]		β	*P*-value	Test of moderators (*P*-value)
		Effect size	*P*-value			
Preweaning TDMI (kg/d)						
Source						0.47
AH (BL)	8 (17)	0.07 [0.02, 0.12]	0.01			
OH	6 (11)	0.11 [0.04 0.17]	<0.01	0.04	0.35	
Straw	4 (11)	0.06 [−0.02, 0.15]	<0.01	0.00	0.94	
Others	6 (9)	0.03 [−0.04, 0.10]	0.37	−0.04	0.39	
Method						0.35
FC (BL)	10 (18)	0.09 [0.04, 0.14]	<0.01			
TMR	15 (30)	0.06 [0.01, 0.10]	0.02	−0.03	0.35	
Starter form						0.02
Ground (BL)	8 (19)	0.09 [0.06, 0.13]	<0.01			
Pelleted	8 (14)	0.02 [−0.02, 0.06]	0.31	−0.07	<0.01	
Textured	4 (10)	0.03 [−0.03, 0.08]	0.28	−0.07	0.05	
Milk level (L/d)						0.02
≤4 (BL)	8 (15)	0.10 [0.05, 0.15]	<0.01			
>4, ≤6	7 (13)	0.11 [0.05, 0.16]	<0.01	0.01	0.90	
>6, ≤8	9 (18)	0.00 [−0.06, 0.05]	0.92	−0.10	0.01	
>8	1 (2)	0.07 [−0.16, 0.30]	0.54	−0.03	0.79	
Forage level (continuous)	13 (38)	0.00 [−0.01, 0.00]	0.05			0.05
Postweaning TDMI (kg/d)						
Source						0.15
AH (BL)	5 (8)	0.39 [0.16, 0.62]	<0.01			
OH	3 (6)	0.28 [0.01 0.57]	0.06	−0.12	0.51	
Straw	2 (4)	−0.05 [−0.37, 0.27]	0.76	−0.44	0.03	
Others	5 (7)	0.17 [−0.06, 0.40]	0.14	−0.22	0.14	
Method						0.49
FC (BL)	5 (7)	0.30 [0.06, 0.54]	0.02			
TMR	9 (19)	0.22 [0.03, 0.40]	0.03	−0.08	0.49	
Starter form						0.01
Ground (BL)	3 (6)	0.57 [0.33, 0.80]	<0.01			
Pelleted	7 (15)	0.12 [−0.05, 0.28]	0.15	−0.45	<0.01	
Textured	1 (2)	0.19 [−0.20, 0.58]	0.32	−0.38	0.10	
Milk level (L/d)						0.04
≤4 (BL)	4 (7)	0.40 [0.13, 0.68]	<0.01			
>4, ≤6	4 (8)	0.37 [0.13, 0.60]	<0.01	−0.04	0.83	
>6, ≤8	5 (11)	0.01 [−0.21, 0.23]	0.90	−0.39	0.03	
Forage level (continuous)	11 (22)	0.00 [−0.03, 0.01]	0.28			0.28
Overall TDMI (kg/d)						
Source						0.13
AH (BL)	8 (16)	0.07 [−0.05, 0.18]	0.26			
OH	3 (7)	0.14 [−0.27 0.12]	0.08	0.07	0.45	
Straw	5 (14)	0.03 [−0.12, 0.19]	0.67	−0.03	0.74	
Others	5 (9)	0.15 [0.02, 0.27]	0.02	0.08	0.05	
Method						0.10
FC (BL)	7 (14)	0.14 [0.05, 0.23]	<0.01			
TMR	13 (32)	0.06 [−0.02, 0.15]	0.12	−0.08	0.10	
Starter form						0.09
Ground (BL)	7 (18)	0.20 [0.08, 0.31]	<0.01			
Pelleted	6 (14)	0.08 [−0.03, 0.19]	0.16	−0.12	0.14	
Textured	4 (11)	−0.03 [−0.20, 0.14]	0.74	−0.23	0.03	
Milk level (L/d)						0.11
≤4 (BL)	8 (15)	0.17 [0.06, 0.27]	<0.01			
>4, ≤6	7 (18)	0.12 [0.00, 0.24]	0.05	−0.05	0.52	
>6, ≤8	5 (10)	−0.03 [−0.17, 0.11]	0.64	−0.20	0.02	
>8	1 (3)	0.01 [−0.25, 0.27]	0.94	−0.16	0.26	
Forage level (continuous)	15 (39)	−0.01 [−0.01, 0.01]	0.32			0.32

[1]TDMI = total DMI; AH = alfalfa hay; OH = oat hay; FC = free choice; milk level = the milk replacer used in several investigations with varying DM were adjusted and harmonized (12.5% DM); Note: 12.5% DM was the default for articles utilizing pasteurized milk and other milk with an unknown DM content; *s* = number of studies; *k* = number of effect sizes; WMD = weighted mean differences between treatment group with forage supplementation and control group without forage, calculated using a robust regression hierarchical model to account for nesting of treatments within study; β = estimated regression coefficient; (BL) = baseline.

Table 4. The effect size estimates of forage on structure growth in dairy calves[1]

Item	$s(k)$	WMD [95% CI]		Variance component		%Var. level 1	%Var. level 2	%Var. level 3
		Effect size	P-value	σ^2_{level2} (P-value)	σ^2_{level3} (P-value)			
Body barrel (cm)								
Weaning	8 (22)	0.26 [−0.88, 1.40]	0.65	—	—	—	—	—
Final	8 (23)	2.24 [0.08, 4.40]	0.04	4.779 (<0.01)	4.903 (0.05)	2.1	48.3	49.6
Body length (cm)								
Weaning	13 (31)	0.20 [−0.26, 0.65]	0.38	—	—	—	—	—
Final	11 (29)	0.64 [−0.01, 1.28]	0.05	0.023 (0.50)	0.027 (0.07)	66.6	0	33.4
Heart girth (cm)								
Weaning	14 (32)	−0.09 [−0.82, 0.64]	0.80	—	—	—	—	—
Final	13 (30)	0.39 [−0.32, 1.10]	0.27	—	—	—	—	—
Withers height (cm)								
Weaning	14 (30)	−0.17 [−0.75, 0.41]	0.55	—	—	—	—	—
Final	12 (28)	0.11 [−0.43, 0.65]	0.67	—	—	—	—	—
Hip height (cm)								
Weaning	12 (32)	−0.04 [−0.58, 0.50]	0.89	—	—	—	—	—
Final	11 (30)	0.32 [−0.30, 0.94]	0.30	—	—	—	—	—

[1]s = number of studies; k = number of effect sizes; WMD = weighted mean differences between treatment group with forage supplementation and control group without forage, calculated using a robust regression hierarchical model to account for nesting of treatments within study; σ^2_{level2} = variance between effect sizes within the same study; σ^2_{level3} = variance between studies; %Var. level 1 indicates the degree to which within-individual differences contribute to the total variation; %Var. level 2 indicates the extent to which differences between treatments or conditions within the same study contribute to the total variation; %Var. level 3 indicates the proportion of total variation attributable to differences between studies.

4.46], P = 0.05) and the ground starter (WMD = 2.48 cm, [0.68, 4.29], P = 0.05) had a greater effect on final body length.

Effect of Forage Provision on Rumen Fermentation Parameters

Table 5 provides the overall effect of forage provision on TVFA, acetate, propionate, butyrate, and A:P in dairy calves. We found a tendency for preweaning TVFA to increase (WMD = 0.31 mmol/L, [0.13, 0.49], P = 0.07) with forage provision. Supplementation with forage in calves decreased TVFA (WMD = 12.57 mmol/L, [−23.76, −1.38], P = 0.03) in the postweaning periods. The pooled estimates showed that forage provision increased the concentration of acetate in the rumen during the preweaning (WMD = by 4.77 mol/100 mol, [2.17, 7.28], P < 0.01) and postweaning (WMD = 4.72 mol/100 mol, [2.01, 7.42], P < 0.01) periods. Compared with the control group, forage provision greatly reduced the ruminal concentration of propionate (WMD = 3.48 mol/100 mol, [−6.32, −0.63], P < 0.01) during the preweaning period. The concentration of butyrate was decreased (WMD = 1.8 mol/100 mol, [1.77, 0.01], P = 0.05) in the postweaning period for calves provided forage. Forage supplementation tended to increase A:P (WMD = 0.36, [−0.01, 0.73], P = 0.06) during the preweaning period, and it increased A:P (WMD = 0.13, [0.01, 0.25], P = 0.04) in the postweaning period. Additionally, as reported in Table 5, significant heterogeneity was observed for pooled TVFA, acetate, propionate and butyrate concentrations and A:P in the preweaning (%Var. level 1 < 14.0%) and postweaning (%Var. level 1 < 29.0%) periods. As the number of studies for these parameters were greater than 8, we conducted a moderator analysis (Supplemental Tables S4, S5, S6, and S7, see Notes). Regarding the TVFA, moderator analysis (Supplemental Table S4) showed that compared with the control group without forage, the FC subgroup (P = 0.03) had a significantly decreased preweaning TVFA, whereas the AH (P = 0.05), OH (P = 0.01), TMR (P = 0.03), FC (P = 0.07) and pelleted starter (P = 0.05) subgroups had decreased postweaning TVFA. Concerning acetate concentration, AH (P ≤ 0.03), pelleted starter (P ≤ 0.01), TMR (P ≤ 0.03), and >6, ≤ 8 L/d milk feeding level (P < 0.01) subgroups had significantly increased both preweaning and postweaning acetate concentrations in calves fed forage (Supplemental Table S5). During the preweaning period, feeding forage as a FC (WMD = 6.15 mol/100 mol, [2.71, 9.58], P < 0.01) and TMR (WMD = 3.63 mol/100 mol, [0.43, 6.83], P = 0.03) had a greater increase on acetate concentration. Calves provided with ground starter had a greater increase in the postweaning concentration of acetate (WMD = 4.24 mol/100 mol, [0.21, 8.28], P = 0.04). For the preweaning propionate concentration, FC (WMD = −3.31 mol/100 mol, [−6.51, −0.12], P = 0.04), TMR (WMD = −3.63 mol/100 mol, [−6.76, −0.49], P = 0.03), pelleted starter (−6.25 mol/100 mol, [−10.43, −2.07], P < 0.01), and the >6 to ≤8 L/d milk feeding level (−5.78 mol/100 mol, [−9.23, −2.32], P < 0.01) subgroups had significantly reduced propionate levels (Supplemental Table S6). Regarding butyrate concentration, the AH (−3.19 mol/100 mol, [−5.73, −0.65], P = 0.02), other forages (−2.86 mol/100 mol, [−3.65, −0.08], P = 0.06), ground starter (−3.05 mol/100

Table 5. The effect size estimates of forage on rumen fermentation parameters in dairy calves[1]

Item	$s(k)$	WMD [95% CI]		Variance component		%Var. level 1	%Var. level 2	%Var. level 3
		Effect size	P-value	σ^2_{level2} (P-value)	σ^2_{level3} (P-value)			
TVFA (mmol/L)								
Preweaning	12 (31)	0.31 [0.13, 0.49]	0.07	8.813 (<0.01)	217.848 (<0.01)	0.2	3.9	95.9
Postweaning	15 (35)	−12.57 [−23.76, −1.38]	0.03	20.939 (<0.01)	385.259 (<0.01)	0.1	5.2	94.7
Acetate (mol/100 mol)								
Preweaning	12 (31)	4.77 [2.17, 7.28]	<0.01	7.841 (<0.01)	11.762 (0.03)	0.8	39.9	59.3
Postweaning	14 (33)	4.72 [2.01, 7.42]	<0.01	4.682 (<0.01)	18.376 (<0.01)	0.2	20.3	79.5
Propionate (mol/100 mol)								
Preweaning	12 (31)	−3.48 [−6.32, −0.63]	0.02	0.000 (0.50)	18.686 (<0.01)	14.0	0	86.0
Postweaning	14 (33)	−1.71 [−4.39, 0.98]	0.21	—	—	—	—	—
Butyrate (mol/100 mol)								
Preweaning	13 (32)	−0.19 [−1.43, 1.05]	0.76	—	—	—	—	—
Postweaning	14 (33)	−1.8 [−1.77, 0.01]	0.05	0.57 (<0.01)	8.61 (<0.01)	0.6	6.1	93.3
A:P								
Preweaning	10 (27)	0.36 [−0.01, 0.73]	0.06	0.033 (<0.01)	0.296 (<0.01)	1.7	9.9	88.4
Postweaning	11 (28)	0.13 [0.01, 0.25]	0.04	0.008 (0.01)	0.025 (<0.01)	29.0	17.7	53.3

[1]TVFA = total VFA; A:P = acetate: propionate ratio; s = number of studies; k = number of effect sizes; WMD = weighted mean differences between treatment group with forage supplementation and control group without forage, calculated using a robust regression hierarchical model to account for nesting of treatments within study; σ^2_{level2} = variance between effect sizes within the same study; σ^2_{level3} = variance between studies; %Var. level 1 indicates the degree to which within-individual differences contribute to the total variation; %Var. level 2 indicates the extent to which differences between treatments or conditions within the same study contribute to the total variation; %Var. level 3 indicates the proportion of total variation attributable to differences between studies.

mol, [−5.70, −0.40], P = 0.03), and >4 to ≤ 6 L/d milk feeding level (−3.67 mol/100 mol, [−6.61, −0.72], P = 0.02) subgroups had a decreased concentration of butyrate during the postweaning period compared the calves without forage. For the A:P ratio, supplementation of calf diet with AH (0.43 mol/100 mol, [0.04, 0.83], P = 0.03), other forages (0.13 mol/100 mol, [0.19, 1.07], P < 0.01), FC (0.58 mol/100 mol, [0.18, 0.98], P < 0.01) increased A:P during the preweaning period (Supplemental Table S7). The postweaning A:P was higher when forage was fed as a TMR (0.14 mol/100 mol, [0.00, 0.27], P = 0.05) and given to calves fed ground starter (0.21 mol/100 mol, [0.05, 0.37], P = 0.01).

Effect of Forage Provision on Nutrient Digestibility

Table 6 provides the overall effect of forage provision on DMD, OMD, CPD, and NDFD in dairy calves. Because there were fewer than 8 separate studies on DMD, OMD, NDFD, and CPD during the preweaning period and the pooled results were not statistically significant, we did not further perform a meta-analysis. Likewise, forage provision had no significant effect on the overall effect of DMD, CPD, NDFD, and OMD in postweaning period.

Forage Level and Growth Performance

Moderator analyses indicated that forage level had a significant effect on preweaning TDMI. Furthermore, we conducted a distinct response analysis to the forage level (Table 7). During the preweaning period, we found a consistent quadratic relationship between the impact of forage level on TDMI (P < 0.01, square root of the estimated residual variance [**Srrv**] = 0.077, R^2 [conditional] = 0.933) and the effect on TDMI, peaking at ~12%. Based on these results, a deeper analysis showed that the connections were consistently quadratic between the effect of AH level and TDMI (P = 0.456, Srrv = 0.066, R^2 [conditional] = 0.931), OH level and TDMI (P = 0.233, Srrv = 0.075, R^2 [conditional] = 0.797), and straw level

Table 6. The effect size estimates of forage on nutrient digestibility in dairy calves[1]

Item	$s(k)$	WMD [95% CI]	
		Effect size	P-value
DMD (%)			
Preweaning	2 (6)	—	—
Postweaning	9 (21)	−0.65 [−2.60, 1.30]	0.49
CPD (%)			
Preweaning	2 (6)	—	—
Postweaning	9 (21)	1.88 [−0.66, 4.41]	0.14
NDFD (%)			
Preweaning	2 (6)	—	—
Postweaning	9 (21)	0.18 [−3.89, 4.25]	0.93
OMD (%)			
Preweaning	2 (6)	—	—
Postweaning	8 (18)	−0.85 [−3.55, 1.84]	0.51

[1]DMD = DM digestibility; OMD = organic matter digestibility; NDFD = neutral detergent fiber digestibility; CPD = crude protein fiber digestibility; s = number of studies; k = number of effect sizes; WMD = weighted mean differences between treatment group with forage supplementation and control group without forage, calculated using a robust regression hierarchical model to account for nesting of treatments within study.

Table 7. Parameters of the linear and quadratic model for relationship between forage supplementation and preweaning TDMI[1]

Equation	n	Model	Intercept			X			X^2			Srrv	R^2 (conditional)
			Coefficient	SEM	*P*-value	Coefficient	SEM	*P*-value	Coefficient	SEM	*P*-value		
TDMI (pre)	67	L	0.998	0.002	<0.01	0.002	0.002	0.095	—	—	—	0.081	0.934
		Q	0.985	0.066	<0.01	0.012	0.004	<0.01	-5.182×10^{-4}	1.83×10^{-4}	<0.01	0.077	0.933
TDMI (pre) AH	25	L	1.096	0.089	<0.01	0.005	0.002	0.013	—	—	—	0.652	0.935
		Q	1.092	0.088	<0.01	0.008	0.005	0.121	-2.245×10^{-4}	3.014×10^{-4}	0.456	0.066	0.931
TDMI (pre) OH	15	L	0.990	0.064	<0.01	0.012	0.005	0.024	—	—	—	0.080	0.745
		Q	0.976	0.069	<0.01	0.029	0.015	0.053	-1.559×10^{-3}	1.279×10^{-3}	0.223	0.075	0.797
TDMI (pre) Straw	16	L	1.009	0.053	<0.01	0.002	0.004	0.612	—	—	—	0.096	0.337
		Q	0.987	0.056	<0.01	0.021	0.010	0.037	-1.223×10^{-3}	5.996×10^{-4}	0.041	0.083	0.567

[1]Srrv = square root of the estimated residual variance; L = linear model; Q = quadratic model.; X = first power of the variable (i.e., the linear term); X^2 = second power of the variable (i.e., the quadratic term).

and TDMI (P = 0.041, Srrv = 0.083, R^2 [conditional] = 0.567). Accordingly, the optimal TDMI for preweaning calves may be achieved with 9% OH and 9% straw. Interestingly, the estimated AH level for best performance for TDMI was 19%, which was much higher than the one suggested for OH and straw levels.

DISCUSSION

Calf Performance

Although Imani et al. (2017) previously explored the effects of forage provision in dairy calves on growth performance and rumen fermentation, our study differed from theirs in several ways. First, they focused on the forage source, forage levels, forage offering methods, the physical form of starter feed, and grain sources. In our study, we expanded on the forage sources, such that instead of only comparing AH against other forages (bromegrass, beet pulp, OH, corn silage, barley straw, and so on), we have included AH, OH, straw, and others as levels of comparison. Furthermore, we explored the role that the milk feeding level might play on response variables in calves fed forages. Second, to the best our knowledge, this is the first meta-analysis to report the effect of forage feeding in calves on nutrient digestibility. Third, we explored the optimal levels for feeding forage on TDMI and growth performance. Fourth, we used the hierarchical 3-level meta-analysis, which increased the precision in estimating the effect sizes and thus improved the interpretation of results and decision making.

Our analysis revealed that forage provision increased TDMI, starter intake, and ADG, and tended to decrease FE during the postweaning period. Several studies have shown that forage feeding was associated with increased TDMI (Hosseini et al., 2016; Movahedi et al., 2017; Bagheri et al., 2021) without necessarily increasing starter intake (Bagheri et al., 2021). However, calves fed forage as a FC had a greater TDMI than those fed as a TMR. Moderator analyses further showed high heterogeneity for TDMI suggesting that the outcomes might have been affected by certain factors such as milk feeding level and calf starter form. Although Imani at al. (2017) reported an increase in starter intake during the overall period, we observed only a tendency toward an increase in the same period, but with a high heterogeneity. Our results might have been a reflection of the greater variability in the treatment durations and an unexplained variability in results among the studies. Indeed, some of the studies reported a significant increase in starter intake only before, whereas others showed an increase only after weaning. Due to the increase in starter intake, concomitant differences were observed in ADG and BW, consistent with Imani et al. (2017), who reported greater ADG in calves fed >10%

as forage. Compared with shorter particles, longer hay particles might remain in the rumen for a longer period of time due to limited digestive capacity and a slow transit rate of digesta in the gut (Hill et al., 2008), resulting in an increase in BW from a larger gut fill (Montoro et al., 2013). A recent perspective and commentary recommended that calves be fed a well-texturized calf starter to optimize functional rumen development and thus limit the necessity of feeding forage or roughage before weaning (Kertz, 2023). No differences were observed in the postweaning NDFD, implying that the DMI and nutrient supply were adequate to support the improved growth observed after weaning (Khan et al., 2016). Alternatively, feeding chopped forage could have improved rumen pH before and after weaning, resulting in greater ADG and starter intake in the postweaning period (Hosseini et al., 2019).

Moderator analyses showed that forage source, starter physical form, forage feeding method, and milk level had no effect on the between-study or within-study heterogeneity of postweaning ADG and final BW, which might be connected to differences in the duration of the experimental period and the age at which calves started feeding on forage (Xiao et al., 2023a). The data revealed that when OH and AH were supplemented in the starter feed, further improvements were observed in TDMI during the preweaning and postweaning periods. The greater TDMI in calves fed either OH or AH could be linked to greater palatability of these forages compared with the rest of the forages tested in this meta-analysis. However, some authors have reported that feeding forages like barley straw could result in greater concentrate intake and growth in calves than when AH is fed (Antúnez-Tort et al., 2023). Compared with AH, the OH showed a higher preweaning TDMI, possibly due to OH being of superior quality, the forage feeding level, the age at which forage was introduced (Hosseini et al., 2016), the treatment duration, or an interaction between these factors.

Effects of forage on starter intake have been studied using different forages such as wheat straw (Hosseini et al., 2019), AH (Beiranvand et al., 2014), and OH (Gasiorek et al., 2020), and under different feeding methods. The results have been inconsistent, with some studies reporting improvement (Beiranvand et al., 2014; Hosseini et al., 2019), and others reporting no improvement in growth and performance parameters. The nutritional profile of the forage, such as higher pectin and lower hemicellulose and NDF contents in AH than in OH, might explain the observed differences in intakes (Gasiorek et al., 2020), as the calves consuming the former could experience reduced emptying of the rumen and hence decreasing intake. Improved understanding of how individual forages contribute to improved growth may shed more light on the importance of forage feeding in dairy calves.

During the postweaning period as opposed to the preweaning period, calves fed ground starter had greater intakes, which could be ascribed to increased palatability of concentrates in the absence of milk derived nutrients. In a recent review, Ghaffari and Kertz (2021) also reported that calves supplemented with hay and fed ground starter ate more starter compared with those fed without. Therefore, although texturized starter has been shown to have more benefits in growing calves, meta-analytic data show that ground starter could be fed with hay and give optimal performance to calves compared with the other starters. Moreover, calves given between 0 and 4 L/d compared with those fed 4 and 6 L/d of milk before weaning realized improved growth advantages (TDMI, starter intake, ADG, and BW) during the postweaning period. To encourage greater concentrate intake, facilitate weaning, and avoid decreased growth, a feasible gradual reduction in the volume of liquid feed fed in the final weeks before weaning has been suggested (de Paula et al., 2017).

Structural Growth

The structural parameters (body barrel and body length) are reliable predictors of the calf's development, management, and feeding. The increase in body barrel could be ascribed to gut fill in calves fed forage (Khan et al., 2012). A 10% forage (AH) consumption has been associated with an increase in gut fill (Castells et al., 2012). In particular, increased TDMI and decreased FE and NDFD in calves fed forage could further consolidate the gut fill. In this meta-analysis, calves fed forage had larger body barrel and length measurements during the postweaning period. This was mainly attributable to improved growth after weaning. In addition, the high heterogeneity of body length was most likely due to the source of forage and feeding method.

Rumen Fermentation Parameters

Rumen fermentation begins early in young calves (Žitnan et al., 1998), with the concentration of VFA reported to increase with age (Beharka et al., 1998; Coverdale et al., 2004). Both concentrates and forage consumption are critical for stimulation of the rumen microbial population that produces end products necessary to initiate rumen epithelial development. Early rumen fermentation is especially possible with concentrates, which have high carbohydrate contents and are fermented rapidly by rumen bacteria in calves, generating abundant

VFA and lactic acid, accompanied by a decrease in pH (Warner et al., 1956, Suárez et al., 2006). Meanwhile, a low amount of saliva is generated in young calves (Kay, 1960), and the rumen epithelium is not fully developed, which might result in limited capacity to absorb the VFA (Schwartzkopf-Genswein et al., 2003).

Our results revealed that VFA concentrations decreased with forage provision in the preweaning and postweaning periods. A higher concentration of acetate and A:P were observed, indicating that forage intake promotes the growth of fibrolytic bacteria in the rumen. Unlike the results of Imani et al. (2017), which showed a trend toward significance, we found a significantly negative effect of forage supplementation on postweaning TVFA. Most studies show a decrease in TVFA in calves fed forage in both pre- and postweaning periods (Castells et al., 2013; Beiranvand et al., 2014; Daneshvar et al., 2015; Hosseini et al., 2019). Our meta-analysis showed that effects of forage feeding on rumen fermentation began in the preweaning period and were enhanced during the postweaning period due to various factors. It was expected that calves fed forage created more VFA than calves fed roughage, as evidenced by a postweaning TDMI 210 g/d higher than that of the controls. However, forage feeding can improve the development of rumen environment, resulting in improved production and absorption of VFA (Silper et al., 2014) through favorable ruminal fermentation, rumination, and optimal ruminal pH.

Indeed, some of the earlier studies argued that the fermentation rate could not be accurately reflected by the concentrations of TVFA in rumen, by reason of their rapid clearance and the greater variability in the volume of rumen digesta liquid (Dijkstra et al., 1993). However, the ratio between individual VFA may indicate the type of fermentation (Gasiorek et al., 2020). As indicated by the outcomes of this meta-analysis, including forage in the starter feed has been shown to increase the concentration of acetate, probably due to the greater growth of cellulolytic bacteria and greater degradation of the forage fiber (Castells et al., 2013). Higher A:P concentrations were observed in the preweaning and postweaning periods, consistent with the study of Gasiorek et al. (2020), who fed OH, but contrary to a study in which calves were fed AH as forage and in which there was a tendency toward decrease (Castells et al., 2013). The increase in the A:P ratio could be ascribed to greater concentration of acetate in the forage fed calves. Both butyrate and propionate from fermentation of dietary concentrates regulate ruminal epithelial differentiation and papilla development (Flatt et al., 1958; Mentschel et al., 2001; Khan et al., 2016). Although propionate concentration decreased in preweaning periods, forage supplementation reduced the concentration of butyrate in the postweaning period only (Terré et al., 2013). More studies are required to understand how changes in papilla development and rumen mass in the young calf and concomitant nutrient intake might influence its digestive and absorptive capacities (Baldwin and Connor, 2017).

Moderator analyses indicated that forage source, feeding method, starter form, and milk level did not influence the effects of forage in calves, which might be linked to the quality of forage, and hence determining the amount of fermentable substrate available and the amount of individual VFA produced in the rumen (Poier et al., 2022). Alternatively, the factors (forage source, feeding method, starter physical form and milk feeding level) we explored might significantly interact with each other, as well as with potentially additional factors (age at which forage was introduced, level of forage feeding, and cut length), leading to high heterogeneity.

Feeding chopped or ground diets results in higher total ruminal VFA concentrations in calves fed concentrates (Coverdale et al., 2004), which subsequently lower rumen pH and populations of cellulolytic bacteria (Beharka et al., 1998). These studies are in conflict with the results observed in the current study, showing a lower TVFA in postweaning calves fed ground starter with forage. Moreover, in terms of overall rumen development in calves fed forage, ground starters showed a greater effect than pelleted and textured starters. This may be due to forage promoting rumination and saliva flow into the rumen (Santini et al., 1983). In our study, providing forage to calves fed ground starter had a greater effect on rumen development during the postweaning period.

Nutrient Digestibility and Milk Yield

Nutrient digestibility along the gut is subject to nutrient sources in dairy calves. Increasing dietary fiber in calf diets can reduce nutrient digestibility in calves (Porter et al., 2007). Several studies have shown that adding fiber to calf diets can reduce OMD and CPD, with no differences observed in DMD, NDFD, and ADFD (Daneshvar et al., 2015; Xiao et al., 2023b) during the postweaning period. Forage provision had no effect on DMD, CPD, NDFD, and OMD in the postweaning period in our study, suggesting forage supplementation might not affect nutrient absorption in the intestinal tract of calves.

Forage Level and Growth Performance

A representative indicator (TDMI) was chosen to investigate the optimal forage level appropriate for calf growth. According to our results, calves fed forage experienced considerable improvements in TDMI; most particularly, the greatest effect forage feeding level was during the preweaning period, which might

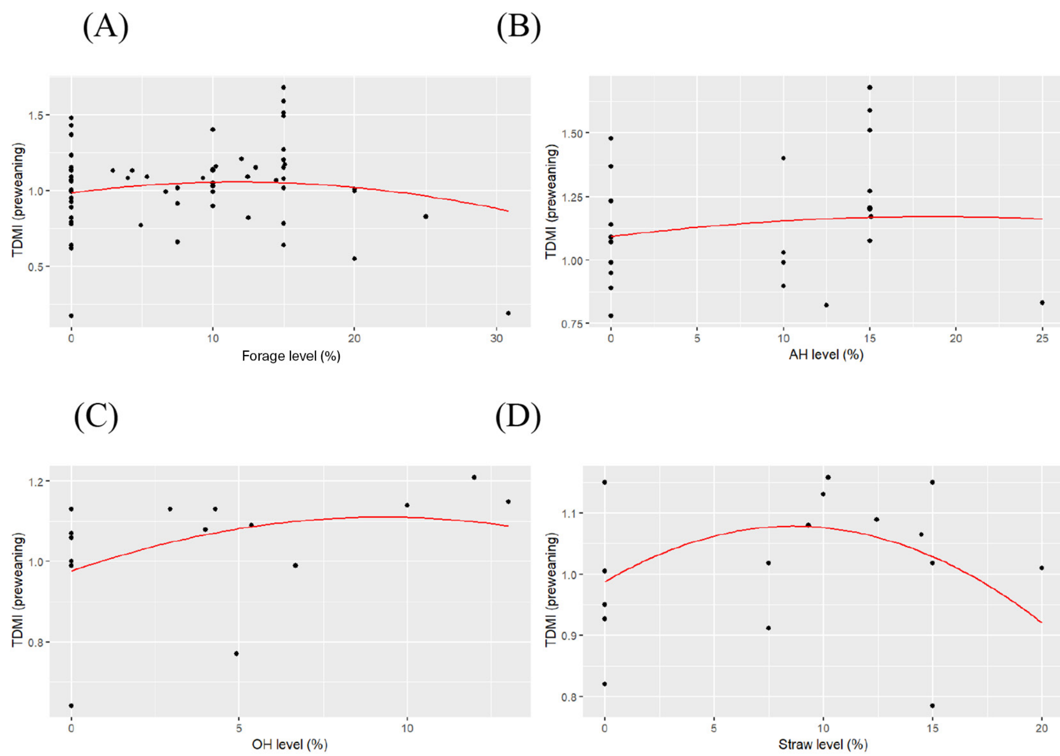

Figure 2. (A) The relationship between forage level and TDMI (kg/d) during the preweaning period. (B) The relationship between AH level and preweaning TDMI. (C) The relationship between OH level and preweaning TDMI. (D) The relationship between straw level and preweaning TDMI.

partially explain the observed positive effects of forage feeding on the rumen environment. In one of the studies, despite offering calves forage up to 30% of the diet on a DM basis, no effect was observed on growth performance (Suárez et al., 2007). On the other hand, providing calves AH up to 25% of DM achieved better calf performance (Nemati et al., 2016). Moderator analysis further showed that forage level was a source of heterogeneity influencing the performance outcomes relative to preweaning TDMI. We further explored the association between forage level and TDMI (Figure 2) using regression analysis, whereby the optimal forage feeding level was estimated to be ~12% DM of the calf diet during the preweaning period. However, the optimal level for OH and straw were determined to be slightly lower, at ~9%, when examining each forage type. Meanwhile, compared with OH and straw, calves could theoretically consume AH at a higher level (19%) in the preweaning period, which was consistent with majority of the trials that designed their studies such that calves were projected to consume 15% of their starter feed as forage. Alfalfa hay is a high-protein forage, but this does not imply that greater consumption corresponds to better performance. It is suggested that higher levels of forage could be used in subsequent studies to improve the accuracy of the regression curves. During the postweaning period, we had limited number of studies in each forage group, which could explain the lack of a significant relationship between TDMI and AH, OH, or straw, resulting in inaccurate regression analysis.

CONCLUSIONS

The current meta-analytic study provides evidence that forage supplementation could benefit calves by improving growth performance and rumen environment. The positive effects on calf growth were especially prominent in calves fed supplemental OH in the starter feed compared with AH or straw. Moreover, calves are more likely to benefit more when forage is fed as a FC rather than as a TMR. The improved performance could be associated with the calves consuming more TDMI in the preweaning period when they are fed forage at the rate of 12% DM of starter feed. To be more specific, calves fed OH or straw should be fed at a rate of 9% DM to achieve optimal performance in preweaning calves. Depending on the real feeding conditions, farms might decide whether or not to supplement forage preweaning.

NOTES

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Nonstandard abbreviations used: %Var. = percentage of variance explained; A:P = acetate/propionate ratio; AH = alfalfa hay; BL = baseline; CPD = CP digestibility; DMD = DM digestibility; FC = free choice; FE = feed efficiency; GMPL = geometrical means particle length; *k* = number of effect sizes; L = linear model; NDFD = NDF digestibility; OH = oat hay; OMD = OM digestibility; Q = quadratic model; *s* = number of studies; srrv = square root of the estimated residual variance; TDMI = total DMI; trt = treatment; TVFA = total VFA; WMD = weighted mean difference; σ^2_{level2} = variance between effect sizes within the same study; σ^2_{level3} = variance between studies.

REFERENCES

Antúnez-Tort, G., A. Bach, C. Cajarville, M. Vidal, F. Fàbregas, M. Ahangarani, and M. Terré. 2023. Benefits of barley straw as a forage for dairy calves before and after weaning. J. Dairy Sci. 106:7578–7590. https://doi.org/10.3168/jds.2023-23401.

Assink, M., and C. J. Wibbelink. 2016. Fitting three-level meta-analytic models in R: A step-by-step tutorial. Quant. Methods Psychol. 12:154–174. https://doi.org/10.20982/tqmp.12.3.p154.

Bagheri, N., A. A. Alamouti, M. A. Norouzian, M. Mirzaei, and M. H. Ghaffari. 2021. Effects of wheat straw particle size as a free-choice provision on growth performance and feeding behaviors of dairy calves. Animal 15:100128. https://doi.org/10.1016/j.animal.2020.100128.

Bahmanpour, A. S., F. Fatahnia, M. Mirzaei, G. Taasoli, H. Mirzaei-Alamouti, and H. R. Jafari. 2023. Milk plane of nutrition and alfalfa hay provision in neonatal Holstein calves: Growth performance, ruminal fermentation characteristics, and blood biochemical attributes. Anim. Feed Sci. Technol. 299:115636. https://doi.org/10.1016/j.anifeedsci.2023.115636.

Baldwin, R. L., and E. E. Connor. 2017. Rumen function and development. Vet. Clin. North Am. Food Anim. Pract. 33:427–439. https://doi.org/10.1016/j.cvfa.2017.06.001.

Beharka, A. A., T. G. Nagaraja, J. L. Morrill, G. A. Kennedy, and R. D. Klemm. 1998. Effects of form of the diet on anatomical, microbial, and fermentative development of the rumen of neonatal calves. J. Dairy Sci. 81:1946–1955. https://doi.org/10.3168/jds.S0022-0302(98)75768-6.

Beiranvand, H., G. R. Ghorbani, M. Khorvash, A. Nabipour, M. Dehghan-Banadaky, A. Homayouni, and S. Kargar. 2014. Interactions of alfalfa hay and sodium propionate on dairy calf performance and rumen development. J. Dairy Sci. 97:2270–2280. https://doi.org/10.3168/jds.2012-6332.

Castells, L., A. Bach, A. Aris, and M. Terré. 2013. Effects of forage provision to young calves on rumen fermentation and development of the gastrointestinal tract. J. Dairy Sci. 96:5226–5236. https://doi.org/10.3168/jds.2012-6419.

Castells, L., A. Bach, and M. Terré. 2012. Effects of feeding different forage sources on rumen fermentation and gastrointestinal tract development of Holstein calves. J. Dairy Sci. 95:286–293. https://doi.org/10.3168/jds.2011-4405.

Castells, L., A. Bach, and M. Terre. 2015. Short- and long-term effects of forage supplementation of calves during the preweaning period on performance, reproduction, and milk yield at first lactation. J. Dairy Sci. 98:4748–4753. 10.3168/jds.2014-9025.

Coverdale, J. A., H. D. Tyler, J. D . Quigley III, and J. A. Brumm. 2004. Effect of various levels of forage and form of diet on rumen development and growth in calves. J. Dairy Sci. 87:2554–2562. https://doi.org/10.3168/jds.S0022-0302(04)73380-9.

Daneshvar, D., M. Khorvash, E. Ghasemi, A. H. Mahdavi, B. Moshiri, M. Mirzaei, A. Pezeshki, and M. H. Ghaffari. 2015. The effect of restricted milk feeding through conventional or step-down methods with or without forage provision in starter feed on performance of Holstein bull calves. J. Anim. Sci. 93:3979–3989. https://doi.org/10.2527/jas.2014-8863.

de Paula, M., C. Oltramari, J. Silva, M. C. Gallo, G. B. Mourão, and C. M. M. Bittar. 2017. Intensive liquid feeding of dairy calves with a medium crude protein milk replacer: Effects on performance, rumen, and blood parameters. J. Dairy Sci. 100:4448–4456. https://doi.org/10.3168/jds.2016-10859.

Dijkstra, J., H. Boer, J. Van Bruchem, M. Bruining, and S. Tamminga. 1993. Absorption of volatile fatty acids from the rumen of lactating dairy cows as influenced by volatile fatty acid concentration, pH and rumen liquid volume. Br. J. Nutr. 69:385–396. https://doi.org/10.1079/BJN19930041.

EbnAli, A., M Khorvash, G. Ghorbani, A. Mahdavi, M. Malekkhahi, M. Mirzaei, A. Pezeshki, and M. Ghaffari. 2016. Effects of forage offering method on performance, rumen fermentation, nutrient digestibility and nutritional behavior in Holstein dairy calves. J. Anim. Physiol. Anim. Nutr. (Berl.) 100:820–827. https://doi.org/10.1111/jpn.12442.

Flatt, W. P., R. G. Warner, and J. K. Loosli. 1958. Influence of purified materials on the development of the ruminant stomach. J. Dairy Sci. 41:1593–1600. https://doi.org/10.3168/jds.S0022-0302(58)91138-X.

Gasiorek, M., B. Stefanska, E. Pruszynska-Oszmalek, J. Komisarek, and W. Nowak. 2022. Effects of the straw inclusion in the diet of dairy calves on growth performance, rumen fermentation, and blood metabolites during pre- and post-weaning periods. J. Anim. Physiol. Anim. Nutr. (Berl.) 106:33–44. https://doi.org/10.1111/jpn.13562.

Gasiorek, M., B. Stefanska, E. Pruszynska-Oszmalek, M. Taciak, J. Komisarek, and W. Nowak. 2020. Effect of oat hay provision method on growth performance, rumen fermentation and blood metabolites of dairy calves during preweaning and postweaning periods. Animal 14:2054–2062. https://doi.org/10.1017/S1751731120000774.

Gelsinger, S. L., A. J. Heinrichs, and C. M. Jones. 2016. A meta-analysis of the effects of preweaned calf nutrition and growth on first-lactation performance. J. Dairy Sci. 99:6206–6214. https://doi.org/10.3168/jds.2015-10744.

Ghaffari, M. H., and A. F. Kertz. 2021. Effects of different forms of calf starters on feed intake and growth rate: A systematic review and Bayesian meta-analysis of studies from 1938 to 2021. Appl. Anim. Sci. 37:273–293. https://doi.org/10.15232/aas.2021-02150.

Hedges, L. V., E. Tipton, and M. C. Johnson. 2010. Robust variance estimation in meta-regression with dependent effect size estimates. Res. Synth. Methods 1:39–65. https://doi.org/10.1002/jrsm.5.

Heinrichs, A. J., S. J. Wells, H. S. Hurd, G. W. Hill, and D. A. Dargatz. 1994. The national dairy heifer evaluation project: A profile of heifer management practices in the United States. J. Dairy Sci. 77:1548–1555. https://doi.org/10.3168/jds.S0022-0302(94)77096-X.

Hibbs, J., H. Conrad, W. Pounden, and N. Frank. 1956. A high roughage system for raising calves based on early development of rumen function. 6. Influence of hay to grain ratio on calf performance, rumen development, and certain blood changes. J. Dairy Sci. 39:171–179. https://doi.org/10.3168/jds.S0022-0302(56)94724-5.

Hill, T. M., H. G. Bateman II, J. M. Aldrich, and R. L. Schlotterbeck. 2008. Effects of the amount of chopped hay or cottonseed hulls in a textured calf starter on young calf performance. J. Dairy Sci. 91:2684–2693. https://doi.org/10.3168/jds.2007-0935.

Hill, T., H. Bateman II, J. Aldrich, and R. Schlotterbeck. 2010. Roughage amount, source, and processing for diets fed to weaned dairy calves. Prof. Anim. Sci. 26:181–187. https://doi.org/10.15232/s1080-7446(15)30578-7.

Hill, T. M., F. X. Suarez-Mena, T. S. Dennis, J. D. Quigley, and R. L. Schlotterbeck. 2019. Effects of free-choice hay on intake and growth of Holstein calves fed a textured starter to 2 months of age. Appl. Anim. Sci. 35:161–168. https://doi.org/10.15232/aas.2018-01826.

Hooijmans, C. R., M. M. Rovers, R. B. De Vries, M. Leenaars, M. Ritskes-Hoitinga, and M. W. Langendam. 2014. SYRCLE's risk of bias tool for animal studies. BMC Med. Res. Methodol. 14:43 https://doi.org/10.1186/1471-2288-14-43.

Horvath, K. C., and E. K. Miller-Cushon. 2019. Evaluating effects of providing hay on behavioral development and performance of group-housed dairy calves. J. Dairy Sci. 102:10411–10422. https://doi.org/10.3168/jds.2019-16533.

Hosseini, S. H., H. Mirzaei-Alamouti, M. Vazirigohar, E. Mahjoubi, and P. Rezamand. 2019. Effects of whole milk feeding rate and straw level of starter feed on performance, rumen fermentation, blood metabolites, structural growth, and feeding behavior of Holstein calves. Anim. Feed Sci. Technol. 255:114238. https://doi.org/10.1016/j.anifeedsci.2019.114238.

Hosseini, S. M., G. R. Ghorbani, P. Rezamand, and M. Khorvash. 2016. Determining optimum age of Holstein dairy calves when adding chopped alfalfa hay to meal starter diets based on measures of growth and performance. Animal 10:607–615. https://doi.org/10.1017/S1751731115002499.

Hunter, J. E., and F. L. Schmidt. 2004. Methods of meta-analysis: Correcting error and bias in research findings. Sage Publications, Thousand Oaks, CA.

Imani, M., M. Mirzaei, B. Baghbanzadeh-Nobari, and M. Ghaffari. 2017. Effects of forage provision to dairy calves on growth performance and rumen fermentation: A meta-analysis and meta-regression. J. Dairy Sci. 100:1136–1150. https://doi.org/10.3168/jds.2016-11561.

Iqbal, Z., M. A. Rashid, T. N. Pasha, and J. Ahmed. 2019. Effects of physical forms of total mixed rations on intake, weaning age, growth performance, and blood metabolites of crossbred dairy calves. Animals (Basel) 9:495. https://doi.org/10.3390/ani9080495.

Jahani-Moghadam, M., E. Mahjoubi, M. H. Yazdi, F. C. Cardoso, and J. K. Drackley. 2015. Effects of alfalfa hay and its physical form (chopped versus pelleted) on performance of Holstein calves. J. Dairy Sci. 98:4055–4061. https://doi.org/10.3168/jds.2014-9126.

Kay, R. N. B. 1960. The rate of flow and composition of various salivary secretions in sheep and calves. J. Physiol. 150:515–537. https://doi.org/10.1113/jphysiol.1960.sp006402.

Kertz, A. 2023. PERSPECTIVE AND COMMENTARY: Dairy calf feeding and nutrition major variables and subsequent performance. Appl. Anim. Sci. 39:449–455. https://doi.org/10.15232/aas.2023-02453.

Khan, M. A., A. Bach, D. M. Weary, and M. A. G. von Keyserlingk. 2016. Invited review: Transitioning from milk to solid feed in dairy heifers. J. Dairy Sci. 99:885–902. https://doi.org/10.3168/jds.2015-9975.

Khan, M. A., D. M. Weary, D. M. Veira, and M. A. G. von Keyserlingk. 2012. Postweaning performance of heifers fed starter with and without hay during the milk-feeding period. J. Dairy Sci. 95:3970–3976. https://doi.org/10.3168/jds.2011-5027.

Khan, M. A., D. M. Weary, and M. A. G. von Keyserlingk. 2011. Hay intake improves performance and rumen development of calves fed higher quantities of milk. J. Dairy Sci. 94:3547–3553. https://doi.org/10.3168/jds.2010-3871.

Lean, I. J., J. E. P. Santos, E. Block, and H. M. Golder. 2019. Effects of prepartum dietary cation-anion difference intake on production and health of dairy cows: A meta-analysis. J. Dairy Sci. 102:2103–2133. https://doi.org/10.3168/jds.2018-14769.

Leibholz, J. 1975. Ground roughage in the diet of the early-weaned calf. Anim. Sci. 20:93–100. https://doi.org/10.1017/S0003356100035042.

Liberati, A., D. G. Altman, J. Tetzlaff, C. Mulrow, P. C. Gøtzsche, J. P. Ioannidis, M. Clarke, P. J. Devereaux, J. Kleijnen, and D. Moher. 2009. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. Ann. Intern. Med. 151:W65–W94. https://doi.org/10.7326/0003-4819-151-4-200908180-00136.

Lin, X., Y. Wang, J. Wang, Q. Hou, Z. Hu, K. Shi, Z. Yan, and Z. Wang. 2018. Effect of initial time of forage supply on growth and rumen development in preweaning calves. Anim. Prod. Sci. 58:2224–2232. https://doi.org/10.1071/AN16667.

Maktabi, H., E. Ghasemi, and M. Khorvash. 2016. Effects of substituting grain with forage or nonforage fiber source on growth performance, rumen fermentation, and chewing activity of dairy calves. Anim. Feed Sci. Technol. 221:70–78. https://doi.org/10.1016/j.anifeedsci.2016.08.024.

Mentschel, J., R. Leiser, C. Mülling, C. Pfarrer, and R. Claus. 2001. Butyric acid stimulates rumen mucosa development in the calf mainly by a reduction of apoptosis. Arch. Tierernahr. 55:85–102. https://doi.org/10.1080/17450390109386185.

Mirzaei, M., M. Khorvash, G. Ghorbani, M. Kazemi-Bonchenari, and M. Ghaffari. 2017. Growth performance, feeding behavior, and selected blood metabolites of Holstein dairy calves fed restricted amounts of milk: No interactions between sources of finely ground grain and forage provision. J. Dairy Sci. 100:1086–1094. https://doi.org/10.3168/jds.2016-11592.

Mirzaei, M., M. Khorvash, G. Ghorbani, M. Kazemi-Bonchenari, A. Riasi, A. Nabipour, and J. Van Den Borne. 2015. Effects of supplementation level and particle size of alfalfa hay on growth characteristics and rumen development in dairy calves. J. Anim. Physiol. Anim. Nutr. (Berl.) 99:553–564. https://doi.org/10.1111/jpn.12229.

Montoro, C., E. Miller-Cushon, T. DeVries, and A. Bach. 2013. Effect of physical form of forage on performance, feeding behavior, and digestibility of Holstein calves. J. Dairy Sci. 96:1117–1124. https://doi.org/10.3168/jds.2012-5731.

Movahedi, B., A. D. Foroozandeh, and P. Shakeri. 2017. Effects of different forage sources as a free-choice provision on the performance, nutrient digestibility, selected blood metabolites and structural growth of Holstein dairy calves. J. Anim. Physiol. Anim. Nutr. (Berl.) 101:293–301.https://doi.org/10.1111/jpn.12527.

NASEM. (National Academies of Science, Engineering, and Medicine. 2021. Nutrient Requirements of Dairy Cattle. 8th rev. ed. National Academies Press, Washington, DC.

Nemati, M., H. Amanlou, M. Khorvash, M. Mirzaei, B. Moshiri, and M. H. Ghaffari. 2016. Effect of different alfalfa hay levels on growth performance, rumen fermentation, and structural growth of Holstein dairy calves. J. Anim. Sci. 94:1141–1148. https://doi.org/10.2527/jas.2015-0111.

Omidi-Mirzaei, H., A. Azarfar, A. Kiani, M. Mirzaei, and M. Ghaffari. 2018. Interaction between the physical forms of starter and forage source on growth performance and blood metabolites of Holstein dairy calves. J. Dairy Sci. 101:6074–6084. https://doi.org/10.3168/jds.2017-13892.

Overvest, M., R. Bergeron, D. Haley, and T. DeVries. 2015. Effect of feed type and method of presentation on feeding behavior, intake, and growth of dairy calves fed a high level of milk. J. Dairy Sci. 99:317–327. https://doi.org/10.3168/jds.2015-9997.

Phillips, C. J. C. 2004. The effects of forage provision and group size on the behavior of calves. J. Dairy Sci. 87:1380–1388. https://doi.org/10.3168/jds.S0022-0302(04)73287-7.

Piray, A., and S. Foroutanifar. 2022. Chromium supplementation on the growth performance, carcass traits, blood constituents, and immune competence of broiler chickens under heat stress: A systematic review and dose–response meta-analysis. Biol. Trace Elem. Res. 200:2876–2888. https://doi.org/10.1007/s12011-021-02885-x.

Poier, G., G. Terler, F. Klevenhusen, S. Sharma, and Q. Zebeli. 2022. Replacing concentrates with a high-quality hay in the starter feed of dairy calves: II. Effects on the development of chewing and gut fermentation, and selected systemic health variables. J. Dairy Sci. 105:3113–3128. https://doi.org/10.3168/jds.2021-21346.

Porter, J., R. Warner, and A. Kertz. 2007. Effect of fiber level and physical form of starter on growth and development of dairy calves fed no forage. Prof. Anim. Sci. 23:395–400. https://doi.org/10.15232/S1080-7446(15)30994-3.

Pounden, W. D., J. W. Hibbs, and C. R. Cole. 1951. Observations on the relation of diet to diarrhea in young dairy calves. J. Am. Vet. Med. Assoc. 118:400–403.

Santini, F., A. Hardie, N. Jorgensen, and M. Finner. 1983. Proposed use of adjusted intake based on forage particle length for calculation of roughage indexes. J. Dairy Sci. 66:811–820. https://doi.org/10.3168/jds.S0022-0302(83)81861-X.

Schwartzkopf-Genswein, K., K. Beauchemin, D. Gibb, D. Crews Jr., D. Hickman, M. Streeter, and T. McAllister. 2003. Effect of bunk management on feeding behavior, ruminal acidosis and performance of feedlot cattle: A review. J. Dairy Sci. 81(Suppl. 2):E149–E158. https://doi.org/10.2527/2003.8114_suppl_2E149x.

Silper, B. F., A. M. Q. Lana, A. U. Carvalho, C. S. Ferreira, A. P. S. Franzoni, J. A. M. Lima, H. M. Saturnino, R. B. Reis, and S. G. Coelho. 2014. Effects of milk replacer feeding strategies on performance, ruminal development, and metabolism of dairy calves. J. Dairy Sci. 97:1016–1025. https://doi.org/10.3168/jds.2013-7201.

St-Pierre, N. R. 2001. Invited review: Integrating quantitative findings from multiple studies using mixed model methodology. J. Dairy Sci. 84:741–755. https://doi.org/10.3168/jds.S0022-0302(01)74530-4.

Suárez, B. J., C. G. Van Reenen, G. Beldman, J. van Delen, J. Dijkstra, and W. J. J. Gerrits. 2006. Effects of supplementing concentrates differing in carbohydrate composition in veal calf diets: I. Animal performance and rumen fermentation characteristics. J. Dairy Sci. 89:4365–4375. https://doi.org/10.3168/jds.S0022-0302(06)72483-3.

Suárez, B. J., C. G. Van Reenen, N. Stockhofe, J. Dijkstra, and W. J. J. Gerrits. 2007. Effect of roughage source and roughage to concentrate ratio on animal performance and rumen development in veal calves. J. Dairy Sci. 90:2390–2403. https://doi.org/10.3168/jds.2006-524.

Tanner-Smith, E. E., and E. Tipton. 2014. Robust variance estimation with dependent effect sizes: Practical considerations including a software tutorial in Stata and SPSS. Res. Synth. Methods 5:13–30. https://doi.org/10.1002/jrsm.1091.

Terré, M., L. Castells, M. Khan, and A. Bach. 2015. Interaction between the physical form of the starter feed and straw provision on growth performance of Holstein calves. J. Dairy Sci. 98:1101–1109. https://doi.org/10.3168/jds.2014-8151.

Terré, M., E. Pedrals, A. Dalmau, and A. Bach. 2013. What do preweaned and weaned calves need in the diet: A high fiber content or a forage source? J. Dairy Sci. 96:5217–5225. https://doi.org/10.3168/jds.2012-6304.

Tipton, E. 2015. Small sample adjustments for robust variance estimation with meta-regression. Psychol. Methods 20:375–393. https://doi.org/10.1037/met0000011.

Türkmen, M., and H. Muruz. 2023. Effects of free-choice provision of different forage sources in preweaning period on performance and some rumen parameters of simmental calves. J. Hell. Vet. Med. Soc. 74:5619–5626. https://doi.org/10.12681/jhvms.28745.

Urie, N. J., J. E. Lombard, C. B. Shivley, C. A. Kopral, A. E. Adams, T. J. Earleywine, J. D. Olson, and F. B. Garry. 2018. Preweaned heifer management on US dairy operations: Part V. Factors associated with morbidity and mortality in preweaned dairy heifer calves. J. Dairy Sci. 101:9229–9244. https://doi.org/10.3168/jds.2017-14019.

Van den Noortgate, W., J. A. López-López, F. Marín-Martínez, and J. Sánchez-Meca. 2013. Three-level meta-analysis of dependent effect sizes. Behav. Res. Methods 45:576–594. https://doi.org/10.3758/s13428-012-0261-6.

Warner, R. G., W. P. Flatt, and J. K. Loosli. 1956. Ruminant nutrition, dietary factors influencing development of ruminant stomach. J. Agric. Food Chem. 4:788–792. https://doi.org/10.1021/jf60067a003.

White, R. R., Y. Roman-Garcia, and J. L. Firkins. 2016. Meta-analysis of postruminal microbial nitrogen flows in dairy cattle. II. Approaches to and implications of more mechanistic prediction. J. Dairy Sci. 99:7932–7944. https://doi.org/10.3168/jds.2015-10662.

Wu, Z. H., A. Azarfar, A. Simayi, S. L. Li, A. Jonker, and Z. J. Cao. 2018. Effects of forage type and age at which forage provision is started on growth performance, rumen fermentation, blood metabolites and intestinal enzymes in Holstein calves. Anim. Prod. Sci. 58:2288–2299. https://doi.org/10.1071/an16576.

Xiao, J., T. Chen, G. M. Alugongo, M. Z. Khan, T. Li, J. Ma, S. Liu, W. Wang, Y. Wang, S. Li, and Z. Cao. 2021a. Effect of the length of oat hay on growth performance, health status, behavior parameters and rumen fermentation of Holstein female calves. Metabolites 11:890. https://doi.org/10.3390/metabo11120890.

Xiao, J., T. Chen, R. Peng, G. M. Alugongo, H. Yang, M. Z. Khan, S. Liu, Y. Ma, J. Wang, W. Wang, Y. Wang, S. Li, and Z. Cao. 2023a. The age at first consumption of forage in calves and its effect on growth and rumination in the short-and long-term. J. Anim. Sci. Biotechnol. 14:107. https://doi.org/10.1186/s40104-023-00885-6.

Xiao, J., T. Chen, R. Peng, G. M. Alugongo, H. Yang, S. Liu, Y. Ma, J. Wang, S. Li, and Z. Cao. 2023b. How neonatal diet affects the long-term development of rumination behavior, rumen fermentation and feed digestion in dairy calves fed a high milk level? Anim. Nutr. 16:326–337. https://doi.org/10.1016/j.aninu.2023.12.003.

Xiao, J. X., L. Y. Guo, G. M. Alugongo, Y. J. Wang, Z. J. Cao, and S. L. Li. 2018. Effects of different feed type exposure in early life on performance, rumen fermentation, and feed preference of dairy calves. J. Dairy Sci. https://doi.org/10.3168/jds.2018-14373.

Xiao, J., M. Z. Khan, G. M. Alugongo, S. Liu, Y. Ma, J. Wang, T. Chen, W. Wang, Y. Wang, and Z. Cao. 2021b. Short-and long-term effects of early life exposure to concentrate or hay on feed sorting and rumen fermentation. Anim. Feed Sci. Technol. 278:115010. https://doi.org/10.1016/j.anifeedsci.2021.115010.

Žitnan, R., J. Voigt, U. Schönhusen, J. Wegner, M. Kokardova, H. Hagemeister, M. Levkut, S. Kuhla, and A. Sommer. 1998. Influence of dietary concentrate to forage ratio on the development of rumen mucosa in calves. Arch. Tierernahr. 51:279–291. https://doi.org/10.1080/17450399809381926.