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Reducing dietary sodium of dairy cows fed a low-roughages diet affect intake and feed efficiency, but not yield



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ABSTRACT

Wastewater from dairy farms has become a major environmental and economical concern. Sodium residue in treated and untreated wastewater from dairy farms used for irrigation can lead to soil and groundwater salinization, with the risk of soil degradation. We examined the effect of reducing sodium fed to mid to late lactating cows from 0.61% (high sodium [HS]) to 0.45% (low sodium [LS]) of dry matter on dry matter intake (DMI), milk and milk-component yields, eating behavior, apparent total track digestibility, feed efficiency, and sodium excretion into the environment. We randomly assigned 28 multiparous high-yielding (> 35 kg milk/d) cows to 1 of 2 treatment groups (LS or HS) in a crossover design, with 7 d of adaptation and 28 d of data collection. Reducing sodium in the diet reduced sodium intake from 171 to 123 g/d while lowering sodium excreted in the manure by 22%. Energy corrected milk (ECM) yield (37.4 kg/d) and sodium excretion in the milk (33.7 g/d) were similar for both groups. The DMI of LS cows was lower than that of HS cows (27.3 vs. 28 kg/d) and consequently, feed efficiency of the LS cows was higher (1.40 vs. 1.35 ECM/DMI). Eating rate, meal and visit frequency, and eating time were similar for both treatments; meal and visit duration were longer for the HS cows, and meal and visit sizes tended to be larger. Digestibility of DM and amylase-treated neutral detergent fiber remained similar. Based on the results of this study, and discussed considerations, we recommend lowering the dietary sodium content for mid to late lactating cows in commercial herds to 0.52% of DM, in order to reduce sodium excretion to the environment via urine.

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1. Introduction

Wastewater from dairy farms has become a major environmental and economic concern. Sodium from treated and untreated wastewater originating from dairy farms and used for irrigation can lead to soil salinization, which carries a significant risk of soil degradation (Daliakopoulos et al., 2016). Disposal of sodium in the environment may affect soil structure by altering the ratios of sodium to calcium and magnesium and by limiting the plants' ability

to absorb water. In addition, sodium from wastewater can reach the groundwater and damage its quality (Meena et al., 2019). In Israel, the common feed for lactating cows is low roughage (30% to 35%) total mixed ration (TMR) supplemented with sodium bicarbonate, sodium chloride, and other minerals and sodium concentration reach up to 0.61% of TMR DM. Consequently, that leads to increased sodium in the farm's effluent. Because sodium is not stored in animal tissues, feeding sodium above needs results directly in increased sodium excretion (NRC, 2001). Reducing sodium levels in dairy farm waste is therefore of great interest. Sanchez et al. (1994) collected and analyzed data from various studies on the effects of macroelement concentrations and interactions in lactating cow feed during the winter or summer. They found a curvilinear relationship between dietary sodium concentration and intake and yield, with the highest DMI (22.5 kg/d) and fat corrected milk yield (23.0–23.5 kg/d) for diets containing 0.6% to 0.8% sodium in dry feed during the winter. A more recent study (Spek et al., 2012) reported an increase in DMI (21.0–21.6 kg/d DM) and a decrease in ECM yield (27.1–25.1 kg/d) with increasing sodium (0.33% to 1.93%

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of DM). A positive linear relationship between drinking (61.7–115.7 L/d) and urinating (18.2–67.7 L/d) and dietary sodium content in their study showed the potential of reducing sodium content in the feed to reduce the amount of excreted sodium. These results are in accordance with Bannink et al. (1999), who analyzed the results of various experiments and showed a strong linear relationship between sodium content in the feed and its excretion in the urine. All of these results support the strategy of reducing sodium in TMR as a method of reducing sodium in dairy farm effluent. However, data on the effect of reduced sodium content in TMR of high-yielding cows fed a low-forage diet (30% to 35% roughages of TMR DM) on feed intake, eating behavior, milk and milk-component yields, and feed efficiency are lacking.

This study hypothesized that reducing dietary sodium will reduce sodium excretion of mid to late lactating without impairing yield. Accordingly, the objective of this study was to measure the effect of reducing sodium chloride added to the TMR on DMI, milk and milk-component yields, ADG, feed efficiency, eating behavior, sodium concentration in the milk, feces, and urine, rumination, and apparent total track in vivo digestibility.

2. Materials and methods

The experiment was approved by the Department of Animal Production, Extension Service, Ministry of Agriculture Institutional Ethics Committee, project number 870-1620-16, according to regulations regarding the protection of animals used for scientific purposes—Directive 2010/63/EU and Israeli law.

2.1. Animals and experimental design

In autumn 2018, 28 multiparous mid-to late-lactating (> 170 DIM) Israeli Holstein cows were selected for the study. Following 2 wk of adaptation, while receiving the high sodium (HS) diet to the individual feeding system, cows were paired into 2 experimental groups with similar (mean ± SD) milk yield (39.9 ± 4.7 kg/d), DIM (238 ± 40), initial BW (655 ± 63.4 kg), and parity (2.9 ± 0.9). One group was fed a low-sodium (LS) TMR, including 0.89 g/kg DM added sodium chloride, while the other was fed the HS TMR, including 4.95 g/kg DM added sodium chloride. The TMR constituents, chemical composition and mineral contents are provided in Table 1. The experiment consisted of 2 periods in a crossover design. In each period, 7 d of adaptation to the treatment diets were followed by 4 wk of data collection of: milk yield and content, DMI, free eating behavior (without tying the cow or sampling it at the feeder), rumination time, and feed efficiency, measured as ECM/DMI. During week 5 of each period, 4 d were assigned for daily sampling of feces and urine from 2 subgroups of 7 cows with similar (average ± SD) milk yield (40.9 ± 5.1 kg/d), DIM (222.2 ± 30.3), and parity (2.6 ± 0.72). The length of the 7-d adaptation period is based on our previous study (Shaani et al., 2017), showing that a 7-d period should be sufficient for rumen adaptation to diet change when altering treatments during trial.

2.2. Cow housing

Cows were housed in the open shade Agricultural Research Organization (ARO) experimental dairy barn (Rishon-Letzion, Israel), which is equipped with a cow recognition system (Halachmi et al., 1998). Cows can move and recumbence freely within the barn while each cow has access to its individual feeder. Since each cow was assigned to a single feeder, hierarchy interruption among cows was minimized, and the system enabled detection of each visit to the feeder. Data collection included: visit and meal frequency, visit and meal size and duration, eating rate, daily eating times, and daily

Table 1

Ingredients, chemical and structural composition, and in vitro digestibility of the low-sodium (LS) and high-sodium (HS) TMR (% of TMR DM).

Item	LS	HS
Ingredients		
Wheat silage	19.5	19.5
Wheat hay	11.6	11.6
Clover hay	1.7	1.7
Corn grain, ground	24.2	24.2
Corn gluten feed	13.3	13.3
Wheat grain, ground	6.7	6.7
Dried distillers grains	6.6	6.6
Bran	4.9	4.9
Rapeseed meal	3.4	3.4
Soybean meal	2.3	2.3
Ca-LCFA ¹	1.4	1.4
Whey concentrate	1.4	1.4
Sodium bicarbonate	1	1
Urea	0.3	0.3
Calcium chloride	0.4	0
Calcium carbonate	0	1.3
Limestone ²	1.2	0.2
Sodium chloride	0.089	0.495
Vitamins and trace minerals ³	0.0475	0.0475
Composition		
DM, % of wet TMR	64.8	64.8
Ash	8.38	7.41
CP	16.5	16.5
Ether extract fat	4.79	4.79
aNDF	27.8	27.8
aNDFom	25.0	25.0
NFC	42.5	43.5
Sodium	0.45	0.61
Calcium	1.09	1.18
Chloride	0.64	0.66
Potassium	1.26	1.28
Phosphorus	0.49	0.49
Sulfur	0.27	0.28
Magnesium	0.21	0.22
DCAD ⁴ , meq/kg	169.1	231.9
NE _L , Mcal/kg	1.78	1.78

TMR = total mixed ration; CP = crude protein; aNDF = amylase-treated neutral detergent fiber; aNDFom = ash-free amylase-treated neutral detergent fiber; NFC = non-fiber carbohydrates; DCAD = dietary anion cation difference; NE_L = net energy for lactation.

¹ Calcium salts of long-chain fatty acids.

² Sidanit (Zmitut81 Ltd., Haifa, Israel), containing (% of product): CaO, 54.2; LOI, 42.8; Al₂O₃, 1.2; MgO, 1; Na₂O, 0.3; K₂O, 0.2; SiO₂, 0.1; TiO₂, 0.1; Fe₂O₃, 0.04.

³ Mix containing (g/kg of mix DM): Zn, 24; Fe, 24; Cu, 12.8; Mn, 24; I, 1.44; Co, 0.32; Se, 0.32; 16 MIU of vitamin A; 3.2 MIU of vitamin D₃; and 48 KIU of vitamin E.

⁴ DCAD = (Na⁺ + K⁺) - (Cl⁻ + S²⁻) (NRC, 2001).

feed intake. A visit was defined as eating at least 200 g DM within at least 5 min of staying at the feeder. When the interval between the end of one visit and the beginning of the next one was shorter than 33.0 min, both visits were considered a single meal. Calculation of this critical time interval for this trial was based on methods and equations described previously (BenMeir et al., 2018), in accordance with Tolcamp et al. (1998). All cows were housed in one barn as a single group and had free access to water and to their specific feeder. Each cow was individually fed its TMR daily between 09:00 and 10:00 ad libitum (5% orts).

2.3. Management, BW measurement, and daily rumination times

Cows were milked 3 times daily, at 05:30, 13:30 and 20:30. Milk yield and milk fat, protein, and lactose contents were recorded at each milking by an automatic meter equipped with an online near-infrared spectrometer (Afilab, Afimilk Ltd., Kibbutz Afikim, Israel) as described by Weller and Ezra (2016). Milk samples were collected from 3 consecutive milkings every 10 d and analyzed for milk fat, protein, lactose, and urea by infrared

analysis (standard IDF 141C:2000; IDF, 2000) at the laboratories of the Israeli Cattle Breeders Association (Caesarea, Israel) to validate the results obtained from the automatic meter. Daily BW was recorded by an automatic walk-through scale (Afimilk) 3 times daily, while cows were exiting the milking parlor. All cows were equipped with collar-mounted HR-tags (SCR Engineers Ltd., Netanya, Israel) that monitored and transmitted rumination time (Schirmann et al., 2009). Rumination data were recorded daily during the 5 wk of the experiment by a special sensor that detects the rhythmic movement of this activity. Data were stored in 2-h blocks and wirelessly uploaded to the computer at the milking parlor in real time.

2.4. Sample collection and analyses

The TMR of each treatment was sampled weekly from the individual feeders immediately after feeding, and Orts were collected from each feeder before the following day feeding, pooled weekly, and sampled. The TMR was mixed and pooled for each treatment, and Orts samples were mixed and pooled for each cow during the 2 periods of the experiment to determine DM content, structural and chemical composition of the TMR, and sorting. Fecal grab samples were collected 12 times over 3 consecutive days (at 06:00, 12:00, 18:00 and 24:00) and pooled for each cow. Fecal samples were then dried at 60 °C for 48 h in a forced-air oven and ground to pass through a 1-mm sieve. We determined DM contents of the 2 TMR, Orts and fecal samples by drying in a forced air oven for 48 h at 60 °C. A pooled sample of feces and Orts for each cow in the subgroups from each period, together with pooled TMR, were shipped to Dairy One Forage Laboratory (Ithaca, NY) for content analysis of: OM, CP, ash-free amylase-treated NDF (aNDFom), crude fat, undigested NDF corrected for ash (uNDFom) 240 h and elements (Ca, P, Mg, K, S, Na, and Cl) concentrations (Dairy One Forage Lab, 2020).

During week 4 of each period, milk and urine were collected from the 2 subgroups for each treatment ($n = 14$). Milk was collected from 3 consecutive milkings during the milking, and urine was collected via bladder stimulation in parallel to feces collection. Milk and urine samples were pooled and shipped to the Neve Yaar service laboratory (Ramat Yishai, Israel) for determination of chloride (SM 4500 Cl–B) and sodium (SM 3500 Na–B) concentrations.

2.5. Calculations and statistical analysis

The ratio of the indigestible NDF (iNDF) concentration in the TMR to that in the feces is assumed to be identical to the ratio of daily fecal DM to DMI for each cow, which is the reciprocal of in vivo DM digestibility according to the following equation (Adin et al., 2009):

$$\text{DM digestibility} = 1 - [\text{intake iNDF (\% of DM)}/\text{fecal iNDF (\% of DM)}],$$

where intake iNDF = $[\text{TMR delivered (kg DM/d)} \times \text{iNDF in TMR (\% of DM)} - \text{Orts (kg DM/d)} \times \text{iNDF in Orts (\% of DM)}]/[\text{TMR delivered} - \text{Orts}]$ (kg DM/d).

The apparent digestibility values of each chemical component (i.e., DM, CP, ether extract, NDF, and non-fiber carbohydrates [NFC]) and minerals (Ca, P, Mg, K, S, Na, and Cl) were calculated for each cow using the proportion between its intake in Orts and fecal output according to the equation presented in Adin et al. (2009). Urine volume was estimated using the following equation (Bannink et al., 1999):

$$\text{Uvol} = 1.3441 + \text{DMI} \times (1.079 \times \text{Na\%} + 0.5380 \times \text{K\%} + 0.1266 \times \text{N\%}) - \text{uMilk} \times (0.1216 + 0.0275 \times \text{MP\%})$$

where K%, Na% and N% = percentage of K, Na and N, respectively, in the dietary DM; uMilk = uncorrected milk yield (kg/d); and MP% = percentage of protein in milk.

Yield of ECM was calculated, based on data from each milking, as:

$$\text{Yield ECM (kg/d)} = \text{Milk yield (kg/d)} \times \{[0.3887 \times \text{Milk fat (\%)}] + [0.2356 \times (\text{Milk protein (\%)})] + [0.1653 \times \text{Milk lactose (\%)}]\}/3.1338.$$

Average daily gain (ADG, kg/d) calculated as the slope of the regression of daily weight data against days in trial.

To compare the groups receiving LS or HS TMR, the following parameters were summarized daily for each cow: DMI, milk and milk-component yields, ECM, ECM/DMI, eating behavior parameters, and daily rumination time. Data were analyzed using the mixed model procedure in JMP (SAS., 2016). Treatment, period, and their interaction were used as fixed effects, cow nested within treatment \times period was a random effect, and day served as a repeated measures factor. The parameters ADG, sodium and chloride in the urine, milk and feces, and in vivo digestibilities summarized by a cow, and comparisons of means between dietary treatments were analyzed using a similar model. Since those variables were measured once per cow per period, we did not include repeated measure factor. Chemical compositions of HS and LS TMR were compared by Student's *t*-test. The standard error of the mean was calculated for each trait, separately for each treatment.

3. Results

3.1. Effect of reducing sodium in the TMR on feed intake and behavior, yield and efficiency

Cows had lower daily DMI ($P < 0.01$, Table 2) when fed the LS TMR as compared to the HS TMR. The lower DMI was manifested in shorter visit and meal duration ($P < 0.01$), and a tendency ($P < 0.10$) toward smaller intake at each visit and meal (Table 2). Eating rate, daily eating time and meal and visit frequency remained similar for

Table 2

Comparison of intake, milk and milk-component yields, daily gain, efficiency, and eating behavior of cows receiving the low-sodium (LS) or high-sodium (HS) TMR.

Item	LS	HS	<i>P</i> -value
Number	28	28	
DMI, kg/d	27.3 \pm 0.14	28.0 \pm 0.14	0.01
ECM, kg/d	37.6 \pm 0.21	37.2 \pm 0.21	0.53
ECM/DMI	1.40 \pm 0.01	1.35 \pm 0.01	0.02
Milk, kg/d	37.9 \pm 0.23	37.6 \pm 0.23	0.38
Milk fat, %	3.98 \pm 0.01	3.98 \pm 0.01	0.66
Milk protein, %	3.34 \pm 0.01	3.34 \pm 0.01	0.68
Milk lactose, %	4.79 \pm 0.01	4.78 \pm 0.01	0.23
ADG, kg/d	0.62 \pm 0.13	0.79 \pm 0.13	0.36
Eating time, min/d	213.7 \pm 2.03	216.7 \pm 1.90	0.16
Eating rate, g DM/min	152.6 \pm 1.67	150.8 \pm 1.46	0.21
Meal ¹ frequency, per d	5.43 \pm 0.04	5.47 \pm 0.04	0.74
Meal size, kg DM	3.81 \pm 0.07	3.93 \pm 0.06	0.09
Meal duration, min	34.8 \pm 0.27	36.2 \pm 0.27	0.01
Visit ² frequency, per d	7.97 \pm 0.10	8.12 \pm 0.11	0.21
Visit size, kg DM	5.25 \pm 0.06	5.40 \pm 0.06	0.08
Visit duration, min	24.9 \pm 0.29	25.9 \pm 0.27	0.01
Rumination, min/d	530 \pm 10	531 \pm 10	0.98

DMI = dry matter intake; ECM = energy corrected milk; ADG = average daily gain.

¹ A meal is defined as the sum of close visits initiated less than 33 min after the end of the previous visit. Meal duration is calculated as sum of visits + intervals between visits during an average meal.

² A visit is defined as eating at least 200 g DM within at least 5 min staying at the feeder.

Table 3
Comparison of DM, aNDF, fat, protein, and mineral intake and digestibility of cows receiving the low-sodium (LS) or high-sodium (HS) TMR.

Item	Intake		Unit	P-value	In vivo digestibility, %		
	LS	HS			LS	HS	P-value
Number	14	14			14	14	
DM	27.2 ± 0.21	28.1 ± 0.21	kg/d	0.09	68.4 ± 0.54	69.7 ± 0.51	0.15
aNDF	7.56 ± 0.06	7.81 ± 0.06	kg/d	0.09	51.2 ± 1.02	53.3 ± 1.03	0.17
Crude protein	4.49 ± 0.03	4.64 ± 0.03	kg/d	0.09	66.2 ± 0.70	70.7 ± 0.58	0.01
Ether extract	1.30 ± 0.01	1.35 ± 0.01	kg/d	0.09	87.6 ± 0.57	89.4 ± 0.57	0.39
NFC	11.6 ± 0.09	12.2 ± 0.09	kg/d	0.09	79.7 ± 0.45	78.4 ± 0.51	0.09
Calcium	296.4 ± 2.1	331.6 ± 2.3	g/d	0.01	24.9 ± 1.61	44.7 ± 1.43	0.01
Phosphorus	133.2 ± 0.9	137.7 ± 0.9	g/d	0.09	65.4 ± 0.92	71.0 ± 1.06	0.03
Magnesium	57.1 ± 0.39	61.8 ± 0.41	g/d	0.01	83.5 ± 0.66	84.9 ± 0.61	0.40
Potassium	342.7 ± 2.4	359.7 ± 2.5	g/d	0.01	83.8 ± 0.71	84.1 ± 0.65	0.75
Sodium	122.5 ± 0.9	171.1 ± 1.2	g/d	0.01	73.1 ± 2.61	76.7 ± 1.85	0.08
Sulfur	73.4 ± 0.51	78.7 ± 0.54	g/d	0.01	71.8 ± 0.71	80.8 ± 0.36	0.01
Chloride	174.1 ± 1.2	185.5 ± 1.3	g/d	0.01	76.1 ± 1.48	81.1 ± 0.80	0.01

aNDF = amylase-treated neutral detergent fiber; NFC = non-fiber carbohydrates.

both TMR. Daily milk and milk-component yields, and daily ECM yield remained similar when fed either the LS or HS TMR. Reduced intake of cows fed the LS TMR while milk yield remained similar led to improved feed efficiency in terms of ECM/DMI when fed the LS compared to HS TMR ($P = 0.03$, Table 2). Rumination time was similar for both TMR.

3.2. Effect of reducing sodium in TMR on digestibility

Intake and apparent in vivo total-tract digestibility of chemical components and apparent absorption of minerals for the 2 sub-groups are given in Table 3. Digestibility of CP was lower when cows were fed the LS vs. HS TMR ($P < 0.01$), whereas digestibilities of DM, amylase-treated NDF (aNDF), NFC and ether extract were similar (Table 3). Intake of calcium, magnesium, potassium, sodium, sulfur and chloride were higher when cows were fed the HS TMR ($P < 0.01$, Table 3). Cows showed lower apparent absorption of calcium ($P < 0.01$), phosphorus ($P = 0.03$), sodium ($P = 0.08$), sulfur ($P < 0.01$), and chloride ($P < 0.01$) when fed the LS TMR (Table 3). Digestibility of magnesium and potassium was similar between groups.

3.3. Effect of reducing sodium in TMR on sodium excretion in milk, urine and feces

Sodium and chloride concentrations in the milk, urine, and feces are shown in Table 4. Sodium concentration in the urine was lower in cows fed the LS vs. HS TMR ($P < 0.01$), whereas sodium concentration in the milk and feces remained similar (Table 4). Chloride concentrations in the urine and milk were similar for both TMR treatments, whereas chloride concentration in the feces was higher when cows were fed the LS TMR ($P < 0.01$, Table 4). Estimated urine volume was higher in cows fed the HS vs. LS TMR ($P < 0.01$), and daily excretion of sodium in the urine was lower in the LS TMR group ($P < 0.01$, Table 4). Excreted sodium in the milk and feces and excreted chloride in the urine, milk, and feces were similar for cows in both groups.

4. Discussion

We hypothesized that reducing sodium in the TMR of lactating cows will result in reduced sodium excretion to the environment without negatively affecting milk yield or feed efficiency. Indeed, we found that the amount of sodium can be greatly reduced without affecting milk or ECM yields. A small reduction in DMI with no concomitant reduction in ECM or ADG led to improved efficiency.

Table 4

Sodium and chloride concentrations and total excretion in urine, milk, and feces of cows receiving the low-sodium (LS) or high-sodium (HS) TMR.

Item	LS	HS	P-value
Number	14	14	
Estimated urine ¹ , L/d	33.9 ± 1.14	40.2 ± 1.22	0.01
Urine Na, g/L	1.89 ± 0.17	2.20 ± 0.18	0.02
Urine Cl, g/L	2.14 ± 0.29	2.14 ± 0.25	0.57
Urine Na, g/d	64.1 ± 5.35	88.4 ± 4.57	0.01
Urine Cl, g/d	72.5 ± 11.4	86.0 ± 9.25	0.49
Milk yield, kg/d	38.6 ± 1.24	38.8 ± 1.27	0.86
Milk Na, g/kg	0.89 ± 0.06	0.85 ± 0.05	0.42
Milk Cl, g/kg	1.44 ± 0.06	1.41 ± 0.04	0.52
Milk Na, g/d	34.3 ± 2.25	33.0 ± 1.62	0.56
Milk Cl, g/d	55.6 ± 2.31	54.7 ± 1.50	0.38
Feces, kg DM/d	8.60 ± 0.29	8.51 ± 0.35	0.80
Feces Na, g/kg DM	3.83 ± 0.33	4.30 ± 0.36	0.33
Feces Cl, g/kg DM	4.82 ± 0.02	4.12 ± 0.03	0.01
Feces Na, g/d	32.9 ± 2.78	36.6 ± 4.57	0.31
Feces Cl, g/d	41.5 ± 3.31	35.1 ± 3.95	0.01

¹ Urine volume was estimated as: $Uvol = 1.3441 + DMI \times (1.079 \times Na \% + 0.5380 \times K\% + 0.1266 \times N\%) - uMilk \times (0.1216 + 0.0275 \times MP\%)$, where $Uvol$ = urine volume (kg/d); $K\%$, $Na\%$ and $N\%$ = percentage of K, Na and N, respectively, in the dietary DM; $uMilk$ = uncorrected milk yield (kg/d); and MP % = percentage of protein in milk, as demonstrated by Bannink et al. (1999).

4.1. Effect of treatments on yield, intake, and efficiency

A previous study (Spek et al., 2012) showed that when cows are fed TMR containing 33.8% to 35.8% NDF, there is no effect of increased dietary sodium (0.28% to 1.37% of DM) on milk yield (25.2–25.7 kg/d), and only a small effect on DMI (increasing from 21.0 to 21.6 kg DM with increased sodium). As in their study, DMI intake in our study was lower when cows were fed the LS vs. HS TMR, and this decrease did not affect yield. Reduced DMI with no effect on milk yield resulted in improved efficiency based on ECM/DMI (Table 2), in accordance with our previous studies (Ben Meir et al., 2018, 2021), demonstrating that feed manipulation to reduce DMI of high-yielding lactating cows with low feed efficiency can improve their efficiency. Nevertheless, this effect (improved efficiency due to reduced intake) may depend on the cow's stage of lactation and its metabolic state (mid to late lactation in the current study). In addition, a longer period experiment should be conducted in order to establish the relation between sodium levels and efficiency as a very small change in body reserves (perhaps even not measurable over 4 wk) could account for the ECM/DMI difference. The effect of this DMI reduction on early lactation cows or more productive ones, and specifically when the cow is in negative energy balance postpartum, may reduce milk yield due to a shortage

of energy, and may impair efficiency. Therefore, further research is suggested to establish the effect of reducing sodium on yields and efficiency in an early stage of lactation. The differences in sodium content in this study also affected the dietary anion cation difference (DCAD) (Table 1). A meta-analysis performed by Iwaniuk and Erdman (2015) concluded that increasing DCAD leads to higher DMI and yield. This effect is in accord with the results in the DCAD range of the current study as HS diet (DCAD of 228.1 mEq/kg) cows intake was higher than LS diet (165.3 mEq/kg). Nevertheless, ECM yield for both treatments was similar, and efficiency was lower for the higher DCAD (HS diet) treatment. Murphy et al., 1982 modulated the water intake of lactating cows based on DMI, milk yield, sodium intake, and temperature. According to their equation, reducing dietary sodium intake from 171.1 (HS) to 122.5 (LS, Table 3) together with 0.9 decreases of DMI may reduce water intake by 3.8 kg/d.

4.2. Effect of treatments on *in vivo* digestibility

Reducing sodium in the LS TMR reduced apparent *in vivo* digestibility of CP (Table 3). This might be related to lower AA absorption caused by a shortage of sodium cations involved in the activity of Na⁺/AA symporters located on the apical membranes of intestinal villus cells in the duodenum and jejunum. Sodium ions, moving down the apical membrane, provide the force that drives diffusion of AA across the apical membrane of villus cells of the small intestine (Goff, 2018). Another explanation might be changes in metabolic fecal N caused by differences in DMI or increased loss of N via urine rather than being dumped back to intestines, as demonstrated by Lee et al. (2021) who reported that lowering DCAD from 220 to 150 Meq/kg lowered CP digestibility while increasing feces N and decreasing urine N. Reducing sodium in the LS TMR also led to decreases in other minerals' apparent total-tract absorption, including phosphorus, sulfur and chloride (by 7.9%, 11.1%, and 17.5%, respectively, as compared to the HS control treatment), but mostly calcium (by 44%; Table 3). The lower calcium absorption coefficient of the LS TMR (0.25 vs. 0.45) was likely because of the use of limestone ('Sidanit'; Zmitut81 Ltd., Haifa, Israel) instead of calcium carbonate and calcium chloride mixture, as part of the manipulation aimed to balance chloride levels in the LS diet. This phenomenon appeared in a previous study (apparent absorption coefficients of 0.22–0.30, Ben-Ghedalia et al., 1996) conducted with high-yielding (35–45 kg/d milk) lactating cows. The lower DMI of the LS cows did not affect DM digestibility. This result is in accord with our previous work (Ben Meir et al., 2019), revealing that feed restriction of 13% does not affect DM digestibility.

4.3. Effect of treatments on sodium excretion

Sodium intake of the cows fed the LS diet was 28% lower than for those fed the HS diet (Table 3). Total excreted sodium in milk, feces and estimated urine accumulated to 92.3% of intake for the HS cows and 97.4% for the LS cows. Chloride accumulated to 94.8% and 100.1% for HS and LS diets, respectively. These values may indicate, overall, a good estimation of urine volume of the LS cows and that some sodium and chloride may be stored in gained BW or excreted in the cows' sweat. However, since sodium generally does not accumulate in body stores (NRC, 2001), and based on higher sodium concentration in the HS cows' urine, we can confidently assume that most, if not all of the sodium that was reduced in the feed was also reduced in the cows' and barn effluents, thus making the dairy farm more environmentally friendly.

4.4. Sodium recommendation for TMR

The amount of sodium required for maintenance, growth and gestation (NRC, 2001) is derived from a combination of 2 methodologies: (1) empirical, based on data collected from various trials, which provide different amounts of sodium and measure the effect on intake, milk yield, etc.; this method results in a recommended amount of around 0.6% to 0.7% of TMR DM; and (2) sum of sodium excretion or losses in milk, urine, feces and the body or fetal tissues (collected from slaughterhouse data, House and Bell, 1993), where dietary sodium must exceed the losses. We used the following parameters from the NRC (2001) to calculate the daily sodium requirement: 0.038 g/kg BW for maintenance + 0.1 g/100 kg because the temperature in our barn ranged between 25 and 30 °C, 0.87 g/kg milk based on sodium concentration in the milk in the current study, 1.4 g/kg ADG, and 1.39 g when gestation is between 190 and 270 d. The calculated amount is then divided by the *in vivo* digestibility value of sodium. The sodium requirement based on this calculation averaged around 80.1 g/d, equal to 0.35% of TMR DM, which is lower than the sodium supplied in the LS treatment and lower than the recommended amount based on methodology (1); it is thus likely to cause sodium deficiency. Moreover, reducing sodium by reducing sodium chloride and sodium bicarbonate will reduce absorption and decrease sodium availability even more. One possible reason for the discrepancy between the results using the 2 methods could be the relatively high milk yield (37.7 kg/d) and large size of the animals (670 kg) used in the current study compared to those used for the NRC equation and coefficients. It seems that when considering yield and health of high yielding cows fed low roughage TMR as in the current study, the safest approach is to supply sodium at around 0.6% to 0.7% of TMR DM. Because DMI is correlated to BW and yield (Ben Meir et al., 2018), this should also suit different animal sizes and yields. On the other hand, calculating sodium requirement based on methodology (2) as presented at the NRC (2001) seems less appropriate in the current study conditions. However, when considering the negative effects of excess sodium excretion on the environment, additional studies aimed at establishing accurate calculations of sodium requirements, which can then be implemented in the next edition of the NRC, should be encouraged. Considering the current study results, reducing the TMR sodium to 0.45% seems to have no effect on yield. However, there are 2 major unwanted outcomes that should be further evaluated and considered when applying the results of the current study to other modern dairy farms worldwide: lower DMI, which can be problematic under some circumstances, as explained above, and lower CP digestibility. In the current study, there was no difference in the amount of sodium excreted in the milk or feces between treatments, but daily estimated sodium excreted in the urine was 24.3 g higher with the HS diet. We believe that it is therefore safe to conclude that reducing the amount by 24.3 g/d (down to 0.52% of TMR DM) will be the recommended method to reduce sodium effluent based on both methodologies for lactating cows in similar managements as in the current trial.

5. Conclusions

Reducing sodium in low-roughage (31.1% of DM) TMR fed to high-yielding mid-to late-lactating cows from 0.61% to 0.45% of DM slightly reduced DMI but did not affect the yields of milk or its components. Based on the results and discussed considerations, we recommend lowering the dietary sodium content for mid to late lactating cows in commercial herds to 0.52% of TMR DM in order to decrease the amount of sodium discharged from dairy farms.

Author contributions

Yehoshav A. Ben Meir: methodology, validation, formal analysis, investigation, data curation, writing – original draft. **Yoav Shaani:** conceptualization, methodology, resources, investigation, funding acquisition. **Daniel Bikel:** investigation. **Yuri Portnik:** investigation, resources. **Shamai Jacoby:** resources. **Uzi Moallem:** conceptualization, writing – review and editing. **Joshua Mirona:** methodology, writing – review and editing, supervision. **Eyal Frank:** conceptualization, investigation, validation, project administration, funding acquisition.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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