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The impact of pre-dry-off weather patterns on subsequent lactation udder health in dairy cows, and their comparison with milkability, milk quality and udder health parameters – A pilot study

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Abstract: Environmental conditions are known to influence the dairy cow health, with most research focusing on the detrimental effects of heat stress. However, the impact of non-summer weather patterns in temperate climates on udder health carry-over between lactations is not well understood. This pilot study evaluated the effect of various weather factors (temperature, humidity, precipitation, sunshine) during 1-day to 90-day periods before dry-off on udder health in the first month post-calving (represented by somatic cell count, conductivity, lactose, and mastitis incidence) in 199 Holstein cows in Central Europe. The scope of the experiment was limited to one farm and one year of observations. Moreover, we also evaluated milk quality, milkability, and udder health parameters during the same periods before dry-off on udder health after calving. We aimed to identify viable indicators across available automatically collected data from weather stations and milking parlour analysers. We found that the long-term (30- to 90-day) exposure to colder temperatures, high humidity, and low sunshine duration before dry-off was significantly associated with worse udder health after calving. In contrast, short-term weather conditions (1- to 7-day) had no significant effect. Monitored milk quality and udder health parameters showed a significant relation to udder health after calving during the immediate periods before dry-off, while milkability parameters were insignificant. If lactose was decreased or protein content, conductivity, and somatic cell count were elevated during the 1- and 7-day period before dry-off, cows after calving showed worse udder health. These findings identify prolonged cold and damp conditions as a significant environmental risk factor for poor udder health in the subsequent lactation, expanding our understanding beyond the conventional focus on heat stress.

Keywords: climate; Holstein; humidity; mastitis; somatic cell count; temperature

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Environmental conditions are recognised as a major contributor to mastitis risk, with the vast majority of research focusing on the detrimental effects of heat stress (West 2003; Das et al. 2016). High ambient temperatures and humidity, often quantified by the temperature-humidity index, are well-documented stressors that compromise the immune function in dairy cattle (Das et al. 2016; Bagath et al. 2019). The direct and indirect effects of global climate change in combination with ever-increasing weather extremes are serious problems for livestock farming (Gauly and Ammer 2020). Changes in the humidity and wind regimes are expected, along with the increase in temperatures (Hempel et al. 2019). At the same time, Intergovernmental Panel on Climate Change (2021) forecasted in their regional climate projections an increase in mean and extreme precipitation events for Northern and Central Europe, underscoring that future environmental challenges to livestock health will not be limited to heat only. Temperature, humidity, air velocity, and light are four important microclimatic parameters that affect cattle health (Assatbayeva et al. 2022). In this regard, identifying correlations between environmental parameters and physiological reactions of cattle is a starting point for evaluating their effects on future welfare and milk production of dairy cows (Mylostyvyi and Chernenko 2019). The weather influences the microclimate in the stable, especially in the case of inappropriate management of ventilation. Fluctuations from ideal values significantly increase the incidence of various diseases, such as mastitis (Assatbayeva et al. 2022).

Studies have already identified various cow-, farm-, and management-related factors before and during the dry period that can affect the rate of clinical mastitis after calving (Green et al. 2007; Wagemann-Fluxa et al. 2024), and environmental factors like weather patterns can also play a role. The intensive research focus on heat stress may obscure the impact of other climatic challenges prevalent in temperate zones. Wet conditions and high humidity increase the pathogen loads in the air and the proliferation of environmental mastitis pathogens in bedding (Watson 2015). Cold weather can act as a cumulative stressor, affecting the cow's overall physiological and immune status (Debnath et al. 2024).

While some studies have noted higher mastitis incidence during wet seasons (Nobrega and Langoni 2011), or higher subclinical mastitis rates correlated with high humidity and lower temperatures (Correa et al. 2024), the relative importance and carry-over effects of these prolonged, non-heat-stress weather patterns from the pre-dry on the subsequent lactation udder health remain largely unexplored.

Moreover, selective dry-off treatment has been widely applied across EU dairy farms, which is a switch from blanket antimicrobial dry cow treatment. The success of selective dry-off relies on the correct selection of criteria to identify cows with mastitis for antimicrobial treatment. These criteria mostly include somatic cell count, bacterial cultivation, or milk yield, although more parameters, like weather conditions, might be viable for use in practice.

This study aimed to analyse weather and climate factors in various periods before dry-off to find out if they significantly affected udder health after calving. Milk quality, milkability, and udder health parameters during the same pre-dry-off periods were also evaluated to serve as a comparison to the weather effects.

MATERIAL AND METHODS

This experiment was carried out in accordance with Czech legislation for the Protection of Animals against Cruelty (No. 246/1992) and with Directive 2010/63/EU on the Protection of Animals Used for Scientific Purposes.

Farms and animals. The study was conducted on a commercial dairy farm with Holstein cows in the Central Bohemian region of the Czech Republic. The cows were housed in a modern stable with free-stall housing, an active ventilation system, and recycled manure solids as bedding. The farm is located 412 m above sea level in the moderate climate zone of Central Europe. Cows were milked twice a day in a herringbone parlour and were fed *ad libitum*. The total mixed ration was formulated to exceed requirements for lactating Holstein cows. The average daily milk yield of the herd during the monitored period was 31.82 kg with 4.05% fat content, 3.65% protein content, and 186 thousand somatic cells per ml.

The farm used blanket dry cow treatment. The dry period was approximately 60 days long. In total, 199 Holstein cows (first lactation = 83; second lactation = 48; third and higher lactation = 68) were monitored within a year from June 2020 to June 2021. Cows in our study calved from September 9, 2020 to May 14, 2021. Cows calving between June and August were excluded from this analysis to specifically isolate the effects of non-heat-stress weather patterns on post-calving udder health and to avoid the well-documented, confounding effects of periparturient heat stress on udder health.

Experimental design. The experiment was designed to evaluate the effect of weather conditions (specific parameters defined in data collection) before dry-off (in 1-day, 7-day, 30-day, and 90-day periods) on udder health during the first month after calving (represented by average SCC, conductivity, lactose, and incidence of clinical mastitis). The 1-day and 7-day periods were chosen to evaluate immediate, short-term triggers, while the 30-day and 90-day periods were selected to assess the impact of longer-term, cumulative environmental exposure. Furthermore, the effects of udder health, milkability, and milk quality parameters (specific parameters defined in data collection) on udder health were evaluated during the same periods before dry-off during the first month after calving. Various periods before dry-off were evaluated with the aim of identifying periods with a significant impact on udder health in the following lactation.

Data collection. A comprehensive set of weather variables, which are routinely collected by weather stations, was initially assessed to avoid prejudging which factor (temperature, humidity, precipitation, wind, or sunshine) might be biologically the most relevant. Weather parameters such as average daily wind speed (m/s), maximum wind speed (m/s), average daily relative humidity (%), daily total precipitation (mm), daily total sunshine duration (hours), average daily air temperature (°C), maximum daily air temperature (°C) and minimum daily air temperature (°C) were obtained from the nearby (6 km) monitoring station of the Czech Hydrometeorological Institute, namely from the Lany station (ID: P01LANY01). While this provides a reliable measure of regional weather, we acknowledge that the in-barn microclimate was not measured and could differ. However, evaluation of the in-barn microclimate was not the aim of this experiment.

Data on the milk quality [fat (%), protein (%), and fat/protein ratio] were obtained from Afilab analysers (Afifarm, Afikim, Israel). Data on milkability [average milk flow (kg/min); partial milk flows during the first two minutes of milking = 0–15 s, 15–30 s, 30–60 s, 60–120 s (kg/min); milking time (min); milk yield (kg); milk yield in the first two minutes of milking (% of total milk yield); occurrence of bimodal milk flow (%); occurrence of delayed milk flow (%)] were obtained from Afilab analysers (Afifarm, Afikim, Israel). The occurrence of bimodal milk flow was detected when two increments of milk flow were followed by a clear drop in milk flow by more than 0.2 $kg.min^{-1}$ within 1 min after the start of milking (Dzidic et al. 2004). The occurrence of delayed milk flow was characterised as no milk flow during the first 30 s of milking. Data on udder health indicators [lactose (%), SCC (thousand cells/ml), electric conductivity (mS), blood in milk (%)] were obtained from Afilab analysers. Monitored parameters from Afilab analysers were measured for each cow for every milking during the monitored period. Data on mastitis incidence were obtained from the veterinary documentation. Clinical mastitis in the first month after calving was diagnosed in 14 out of the 199 tested animals. Information about the animals involved in the experiment was obtained from the farm documentation.

Statistical analysis. The statistical analyses were performed with the SAS software v9.4 (SAS/STAT®; SAS Institute, Inc. Cary, NC, USA). The basic statistics were calculated by the UNIVARIATE procedure. Data had normal distribution, except for mastitis incidence (binary yes – 100/no – 0) and SCC, which were logarithmically transformed. The effect of the monitored parameters of weather, udder health, milk quality, and milkability in 1-, 7-, 30- and 90-day periods before dry-off on the udder health in the first month after calving was evaluated by the GLM procedure using one-factor analysis of variance. Evaluated effects of weather, milkability, udder health and milk quality were averaged for the monitored periods before dry-off (1, 7, 30, and 90 days), and divided into equally sized groups based on the standard deviation (group 1 = $<\bar{x} - ½\ \sigma$; group 2 = $\bar{x} - ½\ \sigma$ to $\bar{x} + 1/2\ \sigma$; group 3 = $>\bar{x} + ½\ \sigma$). The udder health after calving was evaluated during the first month of lactation based on averages of SCC (thousand cells/ml), lactose (%), conductivity (mS), and occurrence of clinical mastitis. The following weather effects were evaluated: daily wind speed, maximum wind speed, average daily relative humidity, daily total precipitation, daily total sunshine duration, average daily air temperature, maximum daily air temperature, and minimum daily air temperature. The following udder health effects were evaluated: SCC, lactose, electric conductivity, and blood in milk. The following milk quality effects were evaluated: fat, protein, and fat/protein ratio. The following milkability effects were evaluated: average milk flow, partial milk flows during the first two minutes of milking, milking time, milk yield, milk yield in the first two minutes of milking, occurrence of bimodal milk flow, and delayed milk flow. Differences between means were evaluated using the Tukey-Kramer test. The significance level $P < 0.05$ was used to evaluate statistical significance.

RESULTS

Monitored weather effects showed the highest significance on udder health after calving during the 90-day period before dry-off (Table 1). Similar trends were also observed for the 30-day period, however, differences between groups in some effects (average daily relative humidity, sunshine duration, average wind speed, and maximum wind speed) were no longer statistically significant and only showed tendencies. Weather parameters during 1-day and 7-day periods before dry-off did not show any significant effect on udder health after calving.

We observed significant differences in temperature effects (minimal, maximal, average) on so-

Table 1. The effect of weather conditions 90 days before dry-off on udder health in the first month after calving (n = 199 cows)

Effect	Groups	SCC LSM	Lactose (%) LSM	Conductivity (mS) LSM	Mastitis incidence (%) LSM
Minimum daily air temperature (°C)	<3.08	219.92^{a}	4.93^{a}	8.56	7.58
	3.08–10.64	159.73^{b}	4.99^{b}	8.60	7.81
	>10.64	163.10^{b}	4.95^{a}	8.63	5.80
Maximum daily air temperature (°C)	<8.77	219.92^{a}	4.93^{a}	8.56	7.58
	8.77–21.95	160.81^{b}	5.00^{b}	8.60	7.94
	>21.95	162.09^{b}	4.95^{a}	8.62	5.71
Average daily air temperature (°C)	<5.77	219.92^{a}	4.93^{a}	8.56	7.58
	5.77–15.69	155.06^{b}	5.00^{b}	8.60	7.25
	>15.69	168.41^{b}	4.95^{a}	8.62	6.25
Average daily relative humidity (%)	<72.71	168.05^{a}	4.95^{a}	8.64	6.56
	72.71–88.01	161.14^{a}	4.99^{b}	8.60	8.45
	>88.01	213.43^{b}	4.93^{a}	8.55	5.97
Daily total precipitation (mm)	<1.50	218.94^{a}	4.92^{a}	8.57	7.69
	1.50–2.06	169.73^{b}	4.96	8.63	7.46
	>2.06	155.06^{b}	4.98^{b}	8.58	5.97
Daily total sunshine duration (hours)	<2.11	215.18^{a}	4.93^{a}	8.55	6.06
	2.11–6.54	161.23^{b}	4.99^{b}	8.60	8.45
	>6.54	166.82	4.95^{a}	8.63	6.45
Average daily wind speed (m/s)	<1.60	161.75	4.96	8.61	6.67
	1.60–1.68	170.51	4.98^{a}	8.59	8.11
	>1.68	210.29	4.93^{b}	8.58	6.15
Maximum wind speed (m/s)	<7.32	218.68^{a}	4.94	8.58	4.41
	7.32–8.23	162.37^{b}	4.98	8.58	12.70
	>8.23	160.19^{b}	4.95	8.62	4.41

^{a,b}Different letters in columns within the effect represent statistically significant differences ($P < 0.05$)

LSM = least square means; SCC = somatic cell count (thousand cells/ml) matic cell count (SCC) and lactose after calving. Temperature effects showed the same trend, with significantly increased SCC for the lowest temperature group during 90 days before dry-off (+51.51 to 64.86 thousand cells/ml; $P < 0.05$; Table 1). There was no significant difference in SCC between the medium and high temperature groups. Lactose content was highest for medium temperature groups (4.99–5%; $P < 0.05$). Mastitis incidence after calving was not significantly affected by weather before dry-off, probably due to low incidence during the monitored period. However, some trends could be observed, which might prove significant in a larger dataset. Relative humidity during 90 days before dry-off also affected udder health after calving (Table 1). We observed the highest SCC when the average relative humidity was above 88% during 90 days before dry-off (+52.29 thousand cells/ml compared to the medium humidity group; $P < 0.05$). Lactose content was significantly higher in the medium humidity group (4.99%, $P < 0.05$). Daily precipitation and total daily sunshine also significantly affected udder health after calving. The worst udder health (increased SCC, decreased lactose; $P < 0.05$) was observed for low daily precipitation and short sunshine duration during the 90-day period before dry-off (Table 1). The results for wind factors were inconclusive. SCC was not significantly affected, although we observed a trend for higher SCC with more windy weather. This trend was confirmed by lactose content, which was significantly lower if there was windy weather in the 90-day period before dry-off. On the other hand, the maximum wind speed showed opposite results with the lower SCC if the maximum wind speed reached above 7.3 m/s. Conductivity after calving was not affected by any of the evaluated weather effects.

Table 2. The effects of monitored milk quality and udder health parameters 7 days before dry-off on udder health in the first month after calving (*n* = 199 cows)

Effect	Groups	SCC LSM	Lactose (%) LSM	Conductivity (mS) LSM	Mastitis (%) LSM
	<2.04	140.49^{a}	5.01^{a}	8.55	2.90
Log SCC	2.04–2.41	179.96^{a}	4.96^{b}	8.60	10.13
	>2.41	232.02^{b}	4.89^{c}	8.64	6.00
	<4.90	237.52^{a}	4.89^{a}	8.70^{a}	7.58
Lactose (%)	4.90–5.04	163.05^{b}	4.97^{b}	8.53^{b}	10.61
	>5.04	142.61^{b}	5.01^{c}	8.55	2.99
	<8.39	156.22^{a}	4.98^{a}	8.38^{a}	4.62
Conductivity (mS)	8.39–8.99	165.26	4.97^{a}	8.64^{b}	7.58
	>8.99	219.57^{b}	4.92^{b}	8.76^{b}	8.82
	<0.01	170.20	4.98^{a}	8.58	6.06
Blood (%)	0.01–0.03	170.58	4.96	8.52^{a}	10.61
	>0.03	201.51	4.92^{b}	8.69^{b}	4.48
	<4.38	183.91	4.95	8.61	9.09
Fat (%)	4.38–4.71	188.81	4.95	8.66	7.46
	>4.71	169.76	4.97	8.51	4.55
	<3.60	151.81^{a}	5.00^{a}	8.62	5.88
Protein (%)	3.60–3.78	178.58	4.95^{b}	8.63	6.15
	>3.78	213.05^{b}	4.92^{b}	8.54	9.09
	<1.18	203.00	4.93^{a}	8.59	9.09
Fat/protein ratio	1.18–1.27	170.05	4.96	8.64	7.58
	>1.27	169.72	4.98^{b}	8.54	4.48

$^{a–c}$Different letters in columns within the effect represent statistically significant differences ($P < 0.05$)

LSM = least square means; SCC = somatic cell count (thousand cells/ml)

Compared to the evaluation of weather effects, monitored milk quality and udder health parameters during the 1-day and 7-day periods before dry-off showed a more significant relation to udder health after calving. If the udder health indicators (SCC, lactose, conductivity, blood) were elevated (decreased in the case of lactose) in the 7-day period before dry-off, cows after calving showed the worse udder health (Table 2). Significant differences were found for the worst groups (high SCC, low lactose content, high conductivity, high blood content) compared to the medium and the best group in these udder health indicators. The medium and the best group did not differ significantly, however, the trend of better health after calving for the group with the best values for udder health parameters was observed.

Moreover, the majority of these significances were also found with the same trends during the 30- and 90-day period before dry-off. For example, SCC and lactose effects on udder health were significant after calving in all monitored periods before dry-off. Conductivity groups before dry-off showed significant differences in SCC, lactose, and conductivity after calving in all monitored periods before dry-off. Blood content groups showed a significant difference in SCC only in the 1-day period before dry-off, but there were significant differences in lactose content in all periods.

Fat content before dry-off did not significantly affect the udder health parameters after calving in any of the monitored periods. Cows with high protein content (>3.78%) during the 7-day period before dry-off had higher SCC (+61.24 thousand cells/ml; $P < 0.05$) and lower lactose (–0.08%; $P < 0.05$) after calving compared to cows with low protein content (<3.6%; Table 2), and this effect was observed in all monitored periods. The fat/protein ratio before dry-off was significant only for lactose content after calving. Cows with a low fat/protein ratio during the 7-day period before dry-off had the lowest lactose content ($P < 0.05$), and an insignificantly higher SCC (Table 2).

Milk yield and tested milkability parameters (milking time, milk yield in the first two minutes of milking, average milk flow, partial milk flows, occurrence of bimodal milk flows and delayed milk flows) during the 1-day, 7-day, 30-day and 90-day periods before dry-off did not have a significant effect on udder health after calving. The only effect that showed significant differences between groups was average milk flow during the 1-day and 7-day periods before dry-off. Cows with lower milk flow (<1.78 kg/min) during these periods had significantly higher SCC (210.18 vs 157.88 thousand cells/ml; $P < 0.05$) in the first month after calving compared to cows with high milk flow (>2.15 kg/min).

DISCUSSION

The primary and most novel finding of this study is that the long-term exposure to cold, humid, and overcast weather during the 90-day and 30-day period preceding dry-off was significantly associated with poorer udder health in the first month of the subsequent lactation. This contrasts with the vast body of literature that identifies heat stress as the primary environmental threat to udder health in dairy cattle (West 2003; Bagath et al. 2019). Extremes of temperature and humidity are to some extent tied to the season of the year, and they will significantly influence SCC and the total number of bacteria (Bokharaeian et al. 2023). On the other hand, our results suggest that in temperate climates, non-heat stress weather patterns represent a significant, and likely underappreciated, risk factor for the carry-over of udder health problems between lactations.

Several biological mechanisms could explain this association. Firstly, prolonged periods of cold, damp, and low-sunshine weather can degrade the quality of bedding and outdoor loafing areas, creating an ideal environment for the proliferation of environmental mastitis pathogens. Secondly, while not as acute as heat stress, chronic exposure to cold conditions can be a significant physiological stressor, increasing energy expenditure for thermoregulation and potentially diverting resources away from the immune system (Debnath et al. 2024). The effect of climatic variations on various metabolic alterations, including immune system depletion, which consequently favours the occurrence of diseases, is better understood for conditions of high temperatures and humidity when animals suffer from heat stress (Bagath et al. 2019). Either way, a cow entering the dry period in a state of compromised immunity would be more susceptible to new intramammary infections. Udder health can carry over to the next lactation, which we also observed in our results, when the cows with worse udder health parameters before dry-off had worse udder health parameters after calving.

Our findings align with and extend the observations of studies that have linked mastitis incidence to wet seasons. For instance, Nobrega and Langoni (2011) reported a higher incidence of mastitis during the wet season in Brazil. More recently, Correa et al. (2024) observed higher rates of subclinical mastitis associated with high humidity and lower temperatures. Our study builds upon this by pinpointing a specific critical window – the long-term period leading up to dry-off – suggesting that the cumulative effect of these conditions, rather than a short-term weather event, is the key driver. Importantly, our results do not contradict the extensive evidence on heat stress, rather we reveal that the environmental risks in other seasons are different but also significant. The correlation of environmental temperature and humidity to SCC was also observed by Piscopo et al. (2024), however, the authors found that climatic conditions had a stronger effect on milk yield and milk solids.

To contextualise the magnitude of these weather effects, we compared them against known cow-level indicators of udder health. As expected, parameters such as SCC, milk conductivity, and protein content measured in the week before dry-off were strong and immediate predictors of post-calving udder health. This highlights a crucial distinction: weather appears to function as a broad, long-term, herd-level risk factor that sets the stage for infection, while individual milk parameters reflect the acute, cow-level physiological response to the sum of all challenges. This explains why weather data lacks the precision for individual cow decisions, such as in selective dry cow treatment, but is valuable for understanding seasonal risk patterns. Milk parameters strongly related to udder health can be used as criteria in selective dry cow treatment systems. Mostly, SCC is used (Cameron et al. 2015; Kiesner et al. 2016; Vanhoudt et al. 2018) as an increase of SCC during intramammary infections is well documented (Bezman et al. 2015), but in our study conductivity, lactose, and protein content also showed a potential to improve the selection process for dry-off thanks to their strong relation to udder health, as was shown in multiple studies (Nielsen et al. 2005; Bezman et al. 2015; Paudyal et al. 2020). Nielsen et al. (2005) found lower protein and higher lactose content in milk from healthy quarters compared to unhealthy quarters. Higher protein and lower lactose were also observed in the already cited study of Nobrega and Langoni (2011), when they found these changes in milk solids during the wet season, in which the incidence of mastitis was also increased.

Most milkability parameters and milk yield before dry-off were not significantly associated with post-calving udder health in our study. Even though milk yield is generally recommended and used as a criterion in selective dry-off systems (Niemi et al. 2021), average milk flow was the only significant milkability factor, when we found significantly higher SCC and lower lactose content after calving for cows with low average milk flow in the 1- and 7-day periods before dry-off. Lower average milk flow for cows with mastitis was observed in the study of Gasparik et al. (2022). Milk flow characteristics can be used for earlier identification of health problems and specific milk flow characteristics can be risk factors for mastitis (Tancin et al. 2007), however in our study milkability characteristics before dry-off did not affect the udder health after calving.

We are aware of several limitations of this pilot study, and for future studies in this research area, multiple farms should be included, in-barn microclimate should be measured, and more cow-level factors should be evaluated. Despite these limitations, our findings have tangible implications for herd management in temperate climates. While farmers should not use a weather forecast for individual dry cow treatment decisions, they can use seasonal patterns to identify high-risk periods – like particularly cold and wet periods. During these times, management should intensify its focus on environmental hygiene, ensuring cows have access to clean, dry, and well-maintained lying areas to minimise the pathogen challenge. Furthermore, a more conservative strategy for dry-off, like using a lower SCC threshold for selective dry cow therapy, might be warranted during these high-risk seasons. Future research should aim to validate these findings across multiple farms and integrate in-barn sensors with bacteriological and immunological data to precisely elucidate the mechanisms linking cold, damp weather to udder health.

CONCLUSION

Our study identifies prolonged exposure to cold, humid, and overcast weather in the 90-day and 30-day periods preceding dry-off as a significant risk factor for udder health in the subsequent lactation. This finding shifts the scientific focus beyond the well-documented effects of heat stress, highlighting a different, yet critical, environmental challenge in temperate climates. The effect might be caused by cumulative physiological stress on the cow and increased environmental pathogen challenge. While these weather patterns are not precise enough for individual cow selection for selective dry cow treatment, they can help identify high-risk seasons, guiding management to intensify environmental hygiene and adopt more conservative udder health strategies. Even though the weather in the 7-day and 1-day periods before dry-off did not prove to be a useful criterion for dry cow treatment, it is important to continue the research and look for novel criteria that might improve selection for antibiotic or non-antibiotic treatment. Besides the already used SCC, other monitored udder health parameters (conductivity, lactose content) and protein content showed a potential to be included in the selection process.

Conflict of interest

The authors declare no conflict of interest.

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