Journal of Agriculture and Food Research 16 (2024) 101150

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Water footprint of Italian buffalo mozzarella cheese

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ARTICLE INFO

Keywords:
Mozzarella supply chain
DNDC
Green water
Blue water
Grey water

ABSTRACT

This study presents a comprehensive assessment of the Water Footprint (WF) for buffalo mozzarella production and consumption relative to an area in central Italy with a high concentration of buffalo farms. Using the Water Footprint Network (WFN) methodology, the consumption of green, blue, and grey water fractions (Wfc) throughout the supply chain has been examined.

The study encompassed nine buffalo dairy farms, two cheese factories, four retail outlets, and a cohort of 243 consumers, providing a comprehensive overview of the entire process from raw milk production and mozzarella cheese making to the final stage of home consumption. The results of the study were expressed as litres of water per kg of consumed buffalo mozzarella cheese. The total WF was 6820 ± 1490 L per kg of mozzarella, with green, blue, and grey Wfc contributing for 59%, 12%, and 29%, respectively. The green Wfc was predominantly influenced (88%) by off-farm feed. The blue Wfc was also primarily affected by off-farm feed (61%), followed by on-farm crop irrigation, buffalos' drinking water and cheese factory operations. Home consumption had a negligible impact on the overall WF. The grey Wfc brought to light environmental concerns, primarily due to nitrate leaching. Although off-farm crops had a remarkable effect on the grey Wfc, the cultivation of on-farm crops was responsible for 69% of this fraction. In particular, a significant part of the grey Wfc originated from on-farm areas left fallow for parts of the year, leading to no uptake of residual nitrogen by crops.

Adhering to WFN guidelines, this research not only expands knowledge on the WF of buffalo mozzarella, but also highlights critical water hotspots. It underscores the necessity for dairy farmers to refine irrigation and soil management, incorporating precise irrigation and crop rotation strategies, to mitigate the impacts on Wfc efficiently.

1. Introduction

Water scarcity and pollution are pressing global challenges that require informed management and the implementation of sustainable practices, particularly in the agricultural sector, a significant contributor to water consumption [1]. Mekonnen and Hoekstra [2] shed light on this issue by reporting that nearly one-third of the global agricultural water footprint (WF) is due to livestock production. As economic growth shifts consumption patterns towards more water-intensive commodities such as meat and dairy, the demand on freshwater resources is increasing. This trend has heightened awareness among policymakers and governments about the critical need to preserve freshwater resources [3].

Within global dairy production, the role of buffalo farming is emerging as a sector of significant importance. Buffaloes provide approximately 15% of the world's milk production and are renowned for their capacity to efficiently convert fibrous feeds into energy. Moreover, their adaptability to hot and humid environments places them as a strategic resource within agriculture, particularly in areas where climatic conditions challenge other ruminants [4]. Therefore, the sustainable management of water resources in buffalo dairy farming would not support only agricultural resilience but might also contribute to the global efforts in improving water management.

Italy represents the European country with the largest number of buffaloes raised, and the farming system is increasingly oriented toward intensive forms of breeding. Most of the farms, which collectively have more than 400,000 animals belonging to the Mediterranean Italian Buffalo breed, are located in central and southern Italy [5,6].

The WF concept, introduced by Hoekstra and Hung [7] and

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https://doi.org/10.1016/j.jafr.2024.101150
Received 29 January 2024; Received in revised form 15 March 2024; Accepted 2 April 2024
Available online 3 April 2024

expanded by Chapagain and Hoekstra [8], provides a robust framework for assessing and quantifying the impact of human activities on water resources. It measures the blue, green, and grey components of water use, representing the consumption of surface and groundwater, rainwater, and the level of water pollution, respectively. Applied to livestock products and production systems at various scales, the WF concept helps in quantifying the freshwater demand of the livestock sector [3,9], thereby becoming integral in evaluating water use throughout supply chains, shaping management strategies, and guiding policymaking [10].

In the agricultural sector, the accurate quantification of the WF is significantly challenged by the absence of a universally accepted methodology. The guidelines of the Water Footprint Network (WFN) [10] and the ISO 14046 standard [11] are recognized as the leading approaches in this domain [12]. The WFN approach is a volumetric metric and focuses on comprehensive water usage across supply chains, emphasizing resource management and efficiency. In contrast, ISO 14046, grounded in the principles of life cycle assessment (LCA) from ISO 14044, is an environmental impacted-oriented indicator of water use, including water scarcity and pollution factors [13]. Despite these differences, both frameworks contribute valuable perspectives to WF but highlight the ongoing debate over best practices for water use assessment [12]. The choice between volumetric WF and impact-oriented WF should be made based on the study's purpose, as they provide complementary information rather than competing [14,15]. The selection of the WFN approach for this study was made in consideration of its comprehensive analysis of green, blue, and grey water fractions (Wfc), which aligns well with the purpose of quantifying resource management within the buffalo mozzarella production chain.

Only a limited number of studies focused on the WF of both buffalo [16,17] and cattle mozzarella cheese [18,19], and none of the studies relative to buffalo mozzarella adopted a comprehensive production-to-consumption approach.

Addressing these research gaps, this study delves into the production of buffalo mozzarella in a geographic area with a large number of buffalo farms. By adopting the comprehensive WFN approach, this research is aimed at expanding the current knowledge on the WF of buffalo mozzarella, and at providing a clearer picture of resource management within its supply chain. Furthermore, it wishes to highlight hotspots of water use and to provide the basis for informed decision-making aimed at achieving more efficient water use in the buffalo mozzarella production chain.

2. Material and methods

2.1. Goal and scope definition

The primary objective of this study was to quantify the WF associated with the production and consumption of buffalo mozzarella. This assessment was grounded in the WFN standards [10], adopting a comprehensive production-to-consumption approach. Notably, a distinct focus was placed on the WF of various crops used as animal feed.

2.2. Water footprint scope and quantification criteria

The scope and quantification criteria for this study were defined in close alignment with the WFN guidelines and with those utilized in a parallel study by Rossi et al. [20], who investigated the same farms and supply chain considered herein.

Specifically, the primary measure of assessment, has been defined as the litres of water consumed per unit of product: 1 kg of buffalo mozzarella cheese marked by a moisture content of 61% and evaluated after household consumption. Additionally, a secondary measure was established to specifically assess the impact of crop cultivation on the overall WF.

This secondary measure was based on the volume of water used per hectare (m^3/ha) for each crop type cultivated within the farm operations. This approach was chosen to reflect the comprehensive water use across cultivation areas, facilitating a direct comparison of water consumption efficiency irrespective of crop yield. However, recognizing the importance of yield-based water use efficiency, data on water use (m^3/tonne of standardised dry matter DM, considering 35% of DM for silages and 88% of DM for hay) of crop cultivated on the farms were also reported.

This comprehensive WF evaluation extended from raw milk production to home consumption, including stages such as feed production (both on-farm and off-farm), animal husbandry, cheese manufacturing and retails, as depicted in Fig. 1. The following subsections will offer detailed insights into each of these stages, providing a comprehensive overview of the phases considered in the study.

The key inventory information collected in 2022 presented herein represents the mean data for the years 2019–2021, relative to the nine farms under investigation.

2.2.1. Farms description

This study centred on nine dairy farms in the productive district of Amaseno (Frosinone, Italy), roughly 80 km south of Rome. Despite difference in herd size, the nine farms displayed a homogeneity in terms of cultivated crops, housing systems, animal genotypes, and farm management. The herd size across these farms averaged approximately 151 ± 74 buffaloes per farm per year, with an annual replacement rate of around 11 ± 2%.

All the buffaloes involved in the study were fed a total mixed ration twice daily post-milking. The ration was composed primarily of on-farm cereal silage (corn, triticale, and sorghum), and a hay mixture of oats, ryegrass, and clover. For lactating buffaloes and fattening male calves, this ration was supplemented by purchased concentrate feeds. However, male calves typically left the farms approximately 40 ± 10 days after birth, with only a few farms involved in fattening activities.

Each farm-specific dataset, encompassing infrastructure, livestock management, resource inputs, and production outputs, was obtained via questionnaires and dialogues with farmers and managers. The overall average milk yield per buffalo was 8.46 ± 0.51 L/d, featuring a fat content of 8.03 ± 0.29% and protein content of 4.72 ± 0.11%. The overall average lactation length was 262 ± 13 days annually.

The barns under investigation featured concrete floors bedded with straw, which was mechanically removed approximately four or five times per year. Buffaloes were cooled during summer and each farm was equipped with a cooling system and had its own protocol for timing, frequency, length of ventilation, and wetting operations.

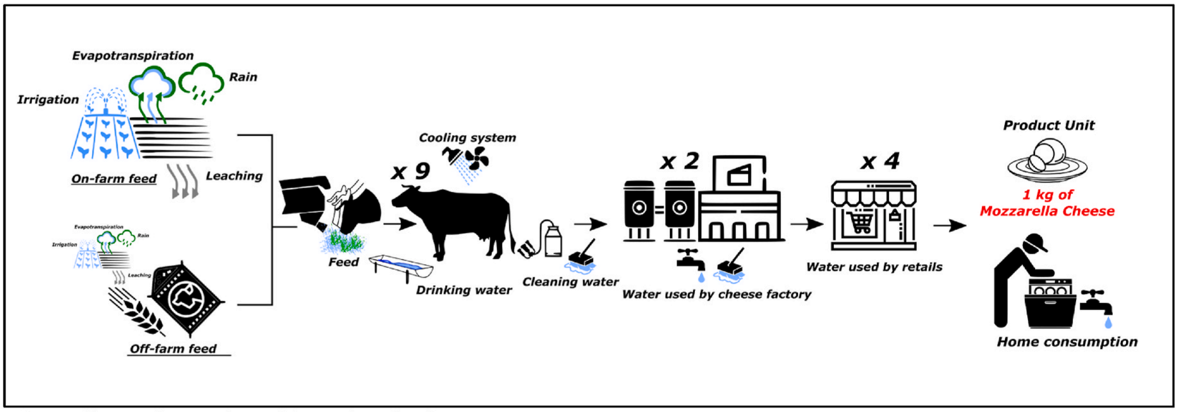
The farms collectively comprised an overall average cultivated area of 33 ± 18 ha. In most instances, an annual crop rotation involving autumn-winter and spring-summer cultivations guaranteed a significant coverage of the animals' nutritional needs. However, certain farm areas that were inaccessible for irrigation, from October to May were under a mono-crop cultivation of a hay mixture (oats, ryegrass, and clover) with the land lying fallow for the rest of the year. Soil operations showed a significant range of variation, from minimal tillage less than 10 cm deep to intensive tillage reaching 40 cm.

The daily average annual (2017–2021) temperatures recorded by the nearest (within a radius of 8.7 ± 1 km of all the investigated farms) weather station (Sonnino, Latina; Lat: 41.369 Lon: 13.204) were 18.7 ± 0.25 °C. During the summer months (June to August), the average temperature rises to 26.9 ± 2.4 °C. The area receives an average annual precipitation of 1028 ± 310 mm, experiences a mean annual wind speed of 0.8 ± 0.03 m/s, and receive a mean annual solar radiation of 14.5 ± 1.0 MJ/m^2/day, with an average humidity level of 70.2 ± 3.7%.

Table 1 and Table 2 provides a comprehensive summary of the key inventory information, representing the mean data for the years 2019–2021 relative to the nine farms under investigation.

2.2.2. Cheese factories description

The study incorporated two cheese factories (CF) processing the milk



x 9 = Indicates the number of farms involved
x 2 = Indicates the number of cheese factories involved
x 4 = Indicates the number of retails involved

Fig. 1. Production phases and reference unit of the buffalo mozzarella cheese water footprint
x 9 = Indicates the number of farms involved
x 2 = Indicates the number of cheese factories involved
x 4 = Indicates the number of retails involved.

Table 1
Summary statistics of herd composition, milk production, and crop management across the nine buffalo farms involved in mozzarella cheese production.

	Farms									
	1	2	3	4	5	6	7	8	9	Mean ± SD
Herd										
Dairy buffalo (n)	178	69	118	149	102	302	152	152	233	**151 ± 74**
Dry buffalo (n)	46	18	37	39	35	79	52	40	61	**39 ± 19**
Heifers (n)	67	26	35	45	31	113	46	68	70	**56 ± 27**
Beef calves (n)	12	–	–	–	–	50	–	25	–	**11 ± 17**
Milk (L/day/head)	9.33	8.02	8.27	8.78	8.71	8.91	8.24	8.23	7.69	**8.46 ± 0.51**
Fat (%)	8.17	8.45	7.79	7.83	8.37	8.02	8.13	7.96	7.55	**8.03 ± 0.29**
Protein (%)	4.73	4.83	4.69	4.51	4.86	4.70	4.78	4.72	4.62	**4.72 ± 0.11**
Average forage ration (%)	75	86	73	75	68	84	79	83	81	**78 ± 6**
Origin of the drinking water	The drinking water for the buffalos is sourced from a well									
Crop										
Farm size (ha)	26	14	30	25	15	73	45	37	29	**33 ± 18**
Irrigated land (%) on tot. cultivated area	69	100	67	28	20	64	44	62	69	**58 ± 24**
Cereal silage (ha)	18	14	20	7	3	47	20	23	20	**19 ± 12**
Hay mixture (ha)	8	–	10	18	12	26	25	14	9	**15 ± 7**
Mineral fertilizer (kg N/ha)	70	95	60	45	65	95	60	95	130	**79 ± 26**
Organic fertilizer (kg N/ha)	210	245	240	255	235	205	240	205	150	**221 ± 32**
On-farm feed (tons/year)	1674	787	1353	595	285	3992	1725	2040	1730	**1576 ± 1085**
Off-farm feed (tons/year)	696	115	482	1236	1219	1345	427	684	1329	**837 ± 456**

The table compiles key parameters from nine different buffalo farms contributing to mozzarella cheese production. The Mean ± SD column provides the average values and standard deviations, summarizing the variability across the surveyed farms.

Table 2
Comparative overview of crop management across the nine buffalo farms involved in the mozzarella production.

Crop type	Irrigated	Tot. fertilizer applied (kg N/ha)	Organic N (%)	Inorganic N (%)	[a]Yield (tonnes DM/ha)
Corn silage	Yes	197	29	71	20
Sorghum silage	Yes	148	72	28	19
Triticale silage	No	173	53	47	15
Hay non-rotation	No	208	87	13	7
Hay in rotation	No	131	78	22	7

[a] Yield is in standardized dry matter (DM) considering 35% of DM for silages and 88% of DM for hay.

from the nine farms enrolled in the study. Although they differed in size, the two CF were representative of buffalo mozzarella production in the area. This is underlined by their respective cheese-making procedures, by the yield of mozzarella cheese (28%), and by mozzarella production being the main product (92 ± 4%) as compared to other dairy products such as provola, scamorza, burrata, and others.

The CF-1, the largest one, operated on an industrial scale, processing a substantial quantity of milk obtained from several buffalo farms that were part of the study. In contrast, the CF-2 was a farm-based CF processing only the milk produced by the same farm.

The two CF were not only involved in the production process, but also played a crucial role in the distribution of the final product. In fact, they sold part of the mozzarella directly to consumers, making them an integral part of the product's journey from farm to table.

Moreover, it is important to highlight that both CF-1 and CF-2 are equipped with advanced wastewater treatment facilities, ensuring environmental compliance by treating effluents from the cheese-making process before discharge.

Finally, our study did not encompass the WF of lactic ferment used in the cheese transformation process. This area represents a potential for future research to complete the WF assessment.

Key data related to the two CF are outlined in Table 3.

2.2.3. Retails

The study included an analysis of four cheese markets to evaluate any water consumption associated with the sale of buffalo mozzarella. Of these markets, two were direct points of sale for the CF participating in the study, while the remaining two were typical urban and mid-sized city supermarkets supplied by the selected CF. This selection of markets was designed to ensure a representative sample of consumers and to provide a more comprehensive characterization of the supply chain.

2.2.4. Final consumption

The study involved 243 consumers through surveys finalized at collecting information on their purchasing and consumption habits of buffalo mozzarella. In other words, the survey aimed to assess the possible consumption of water in the final stages of the product life cycle.

2.3. Water footprint

The WF is a comprehensive indicator encompassing three distinct Wfc: green, blue, and grey, each defined by specific geographical and temporal parameters [10].

Green Wfc is defined as the rainwater absorbed by plants or evaporated from the soil, along with the water incorporated into the harvested crop. However, in our analysis, we deliberately excluded the embedded green Wfc present in the feed provided to the animals. Specifically, we did not account for the water content within the harvested crops used in animal feed, such as the moisture in hay and the moisture in silage. This decision was based on its minimal impact on the overall WF, as established by Grossi et al. [21].

For blue Wfc, encompassing water drawn from surface or groundwater resources and used in processes like soil evapotranspiration, product incorporation, or not returning to the original catchment area within the same period, a range of methodologies were applied. Due to its relatively minor impact, this study, in agreement with findings from Grossi et al. [21], did not include in the calculation the blue Wfc embedded into final products, such as provided feed, milk, or mozzarella.

Lastly, the grey Wfc was assessed, which is defined as the volume of freshwater required to dilute pollutants until the water quality meets acceptable standards. Specifically, to evaluate the impact of buffalo mozzarella production on water quality, this study focused solely on the grey Wfc produced during the production phases of on-farm and off-farm crops. This decision was taken since wastewater treatment processes associated with the farms, CFs, retails, and domestic consumption can significantly reduce, and potentially eliminate, the grey Wfc [10].

Table 3
Comparative production outputs and water resource utilization among the two cheese factories investigate in the study.

	Cheese factories		
	1	2	Mean
Production			
Buffalo raw milk (tonnes/year)	984	229.5	606.7
Processed milk for mozzarella (tonnes/year)	925	204.8	564.9
Processed milk for other cheese (tonnes/year)	59	24.7	41.9
Mozzarella cheese (tonnes/year)	259	57.3	158.2
Water consumption (mc/day)	4.9	10.0	7.45

2.3.1. Green water fraction

In this study, the DeNitrification DeComposition (DNDC) model was employed for quantifying the green Wfc [22]. The DNDC is a process-oriented model that computes the soil evapotranspiration fraction based on factors such as the available water content in the top 20 cm of soil, as well as the presence of surface litter, ponding, or snow [23]. The model, in its most recent iteration (DNDC95), was updated with the FAO Penman-Monteith equation, enhancing its potential evapotranspiration predictions [24].

The DNDC model was first parametrized using farm-specific data regarding crop yield, soil physical and chemical properties, management practices, and local weather conditions (2017–2021). Following this parametrization, crop growth parameters were calibrated employing a "Trial and Error" method, and the Root Mean Square Error (RMSE) statistics were used to align the model's simulated yields with the average annual yields observed by farmers between 2019 and 2021 [25]. A key aspect of this calibration process involved the use of farm-reported crop yield data, measured per hectare. In the DNDC model, crop biomass output is provided as the carbon (C) content within grain, leaf and stem, quantified in kg C/ha. To facilitate comparison between the model's simulated yields and the actual farm-reported yields (expressed in standardised DM), this latter was converted to an equivalent kg C/ha. This conversion was based on the assumption that 1 kg of DM contains 0.4 kg of carbon, as the guideline outlined in the DNDC model manual (available at https://www.dndc.sr.unh.edu/model/GuideDNDC95.pdf, accessed on November 23, 2023). In-depth details on the data inputs utilized for the DNDC modelling are comprehensively documented in the supplementary materials of our previous study [20].

To stabilizes the dynamics of C and nitrogen and minimize initial model setting uncertainties [26,27], the DNDC model was subjected to a five-year pre-run phase, or spin-up time. For each farm, the water resulting from the soil evapotranspiration following the spin-up, in combination with each crop's spatial coverage, was used to account for the annual green Wfc during the modelled crop rotations.

Daily data of temperature, precipitation, wind speed, solar radiation and humidity were sourced from the weather station closest to the investigated area. Soil parameters needed for the DNDC software were obtained from the Harmonized World Soil Database v 1.2 [28], and drainage data was referenced from Panagos et al. [29].

The crop yield calibration within the DNDC model also included parametrization of the irrigation index, which denotes the fraction of water supplied to the soil under conditions of water deficit. The specifics of the irrigation method (i.e., flood, sprinkler, and drip) were determined based on data provided by the farmers. Importantly, following calibration, the DNDC was run with the irrigation index set to zero to specifically identify the green Wfc component of the on-farm crop production [21].

The overall volumes of evapotranspiration green Wfc per hectare modelled by the DNDC were the ones needed to obtain the crop yields (as tonnes of C/ha) declared by the farmers, which also included the fraction of water evaporating during the drying processes. Specifically, once the green water lost from the harvested crop by evapotranspiration was assessed per tonne of standardised DM yielded, a quota of this water was reintegrated to reach the moisture rate of hay (12%) and silages (65%) and considering the green-to-blue ratio resulting from the on-farm crop production [10,21].

2.3.2. Blue water fraction

In this study, the volume of irrigation water required for on-farm crop rotations was estimated by the DNDC model. The DNDC model allows for defining irrigation through an index between 0 and 1. When the model predicts a water stress event, a fraction of water equivalent to the index value is automatically applied to the soil to compensate for the anticipated water deficit. Specifically, during the model runs, the irrigation index was initially set to zero to account for the green Wfc, as outlined in section 2.3.1. The index was then recalibrated to align with farmers' reported crop yields (achieving RMSE <10%) and the irrigation methods utilized (i.e., sprinkler). Ultimately, the DNDC model provided an estimation of the total volume of irrigation water required.

The volumes of blue Wfc lost during the crops drying process were included in the annual volumes of irrigation water totally allocated to the on-farm crop. As for the green Wfc, once the blue water lost from the harvested crop by evapotranspiration was assessed per tonne of standardised DM yielded, a quota of this water was reintegrated to reach the moisture rate of hay (12%) and silages (65%) and considering the green-to-blue ratio resulting from the on-farm crop production [10,21].

Given the limitations on obtaining precise origins of off-farm feed, the methodology for calculating the blue and green Wfc for off-farm feed was adapted to use a combination of average annual volumes of forage and feed purchased by each farmer from 2019 to 2021, alongside global average secondary data on the blue Wfc for each feed type from established research by Mekonnen and Hoekstra [30,31].

The drinking water requirements of lactating buffaloes were estimated from the milk production (kg buffalo^{-1} day^{-1}) and the region-specific average temperature (°C) using the regression function detailed in Krauβ et al. [32]. It is important to note that this regression function was originally developed based on cattle data, as specific data for buffaloes were not available. Similarly, due to the lack of buffalo-specific data, fixed water intake values established for cattle were applied: 45 L per head per day for dry buffaloes and heifers, and 3.1 L per head per day for calves [33].

Additionally, water consumption for sanitation processes, including the cleaning of the milk tank, milking equipment, and milking parlour, was estimated to be 0.63 L per kg of milk, as recorded in the Ecoinvent database [34].

Moreover, literature data [21] were used to account for the water consumed by the cooling system, including showers or misters. This approach was necessary due to the lack of specific water usage data for the cooling systems from the farmers. However, it is important to notice, that this data primarily pertains to cattle, and there may be variations in the cooling requirements and practices for buffaloes.

The daily water demand for these operations, which include the processes of cheese production, equipment cleansing, and sterilization was gathered directly through on-site data collection. However, due to the inability of the CF operators to provide a detailed water consumption breakdown for each specific activity, particularly for the water needed for mozzarella production, they were asked to provide their total daily water usage (Table 3).

In assessing the blue Wfc associated with the buffalo mozzarella supply chain, particular attention was given to the retail and consumption stages. This involved visits to the four selected retail outlets, encompassing both direct points of sale linked to the CF and urban supermarkets. The aim was to observe operational practices and interview staff to ascertain any significant water usage directly attributable to the product's retail.

Regarding consumer water usage, a survey-based approach was employed to gather insights into household water use related to the consumption of buffalo mozzarella. The survey specifically targeted practices that could contribute to the product's overall WF, such as dishwashing after consumption.

2.3.3. Grey water fraction

For the estimation of the grey Wfc associated with on-farm crop production, the DNDC model was employed similar to the approach described for green and blue Wfc. Given that nitrate is the principal pollutant arising from on-farm crop cultivation, the volume of water needed to dilute its concentration to safe levels was calculated. This calculation was based on the modelled annual average amount of nitrate leached from each farm's crop rotations and the European maximum allowable concentration of nitrate (50 mg L^{-1}) in drinking water intended for human consumption [35].

Similarly, determination of green and blue Wfc, the grey Wfc associated with the off-farm feeds was computed using data from Mekonnen and Hoekstra [30,31].

3. Allocation procedures

In the buffalo farms enrolled in the study, the simultaneous production of meat, derived from calves, fattening and culling males, and raw milk, takes place. This needs an allocation of input and output water flows. To ensure an equitable distribution, a biophysical method was employed following recommendation of the International Dairy Federation [36].

The allocation factor for raw milk (AF_{milk}) was then calculated using the formula:

$$AF_{milk} = 1 - 6.04 * BMR$$

Where BMR is the ratio between the mass of live weight of all animals sold per year and the mass of Fat and Protein Corrected Milk (FPCM) sold in the same period. Through the application of this biophysical approach, 78% of flows were assigned to raw milk across the nine farms studied.

Moreover, water flow allocation between buffalo mozzarella cheese and other dairy products such as provola cheese, ricotta and yogurt were determined based on mass considerations. Considering all dairy products, 92% of flows were allocated to buffalo mozzarella cheese.

Lastly, drawing on the findings from Dalla Riva et al. [18], a 5% of the total volume required for a cycle of dishwasher has been allocated to the unit of product considered in this study.

4. Uncertainty analysis

The primary objective of this analysis was to quantify the level of uncertainty associated with the buffalo mozzarella cheese WF, with a focus on different Wfc (green, blue, and grey) and various sources of water use. Uncertainties were estimated by coupling a bootstrap technique with Monte Carlo (MC) simulations in a Python environment, where values within predefined ranges were randomly selected for each parameter [37,38]. This stochastic process was repeated 10,000 times, thereby generating a comprehensive uncertainty distribution.

For on-farm crops, a ±30% variation was applied to green, blue, and grey Wfc (m^3/ha), reflecting precipitation changes from 2017 to 2021. Average values and standard deviations (SD) for crop-specific hectares, milk and crop yield, as well as milk-meat allocation factors were calculated from data collected across the nine farms involved in the study. These statistical measures were included in the MC simulations to provide insights into the variability and central tendency of farm practices and outputs.

Similarly, for off-farm crop, the MC simulations accounted not only for the Wfc global averages (m^3/tonne) as provided by Mekonnen and Hoekstra [30,31] but also for the average and SD quantities of off-farm crop used per litre of milk produced by the nine farm and the associated milk-meat allocation factors. A variability of ±30% was adopted to the Wfc global averages for these off-farm crop, in alignment with the guidance from Zhuo et al. [39], which suggested that uncertainties in climatic inputs could lead to an average uncertainty of ±30% in the total crop WF. This comprehensive approach ensures that the MC simulations reflect both the specific quantities of off-farm crops used by the investigated farms and the broader climatic uncertainties affecting off-farm crop WF.

A ±9% variation was applied, based on the study by Waltner et al. [40], to reflect the uncertainty in the water requirements of buffalo drinking. For the activities within the CFs, a broader variation of ±50%, grounded in primary data obtained from the facility, was considered.

The allocation factor to buffalo mozzarella cheese for water usage within the CF was set at 92%, as informed by the factory owner. Based on the owner considerations, to accommodate potential variability in operational practices, this factor was allowed to fluctuate within a range of ±4%.

For estimating water usage in activities such as the cleaning of the milking parlour and the operation of cooling systems, based on experts' knowledge, a conservative margin of ±10% was adopted. This margin of variation was also applied to the estimated water requirement for a cycle of a dishwasher in the context of home consumption of mozzarella cheese, reflecting the acknowledgment of variability in consumer practices. The allocation factor determining the portion of water attributed to mozzarella dishes was similarly subjected to a variation of ±10%, ensuring that the analysis accommodates a realistic spectrum of water use patterns across the production and consumption phases.

The performed MC analysis aimed to evaluate uncertainties and in calculating the aggregate median, 25th percentile, and 75th percentile for each main source of the buffalo mozzarella cheese WF.

For additional insights and access to the python code used in this analysis, refer to the following GitHub link: https://github.com/Giampiero-G/Bootstrap-technique-with-Monte-Carlo-simulations.git.

5. Results

5.1. Water footprint of mozzarella cheese

The total WF for buffalo mozzarella was determined to be 6820 ± 1490 L per kilogram, with the green, blue, and grey Wfc contributing 59%, 12%, and 29%, respectively (Table 4). In the investigation of the four selected retail outlets, no significant water consumption was detected directly associated with the sale of buffalo mozzarella. This indicates that the retail stage of the mozzarella supply chain does not contributes to the overall buffalo mozzarella WF. Consequently, the percentage contribution of the different phases in the production of buffalo mozzarella cheese to the total WF can be segmented as follows: off-farm crops (~68%), on-farm crops (~31%), barn operations (~0.5%), cheese factory activities (~0.3%), and household consumption (~0.01%).

Table 4
Comprehensive analysis of water usage distribution in buffalo mozzarella production: Detailed breakdown of green, blue, and grey water fractions and their impact on total water footprint.

Water fractions	L water/kg mozzarella	Incidence on subtotal	Incidence on tot.
Green water			
On-farm crop	503 ± 158	12%	7%
Off-farm crop	3522 ± 936	88%	52%
Subtotal	*4025 ± 914*	*100%*	*59%*
Blue water			
On-farm crop	266 ± 121	33%	4%
Off-farm feed	500 ± 356	61%	7 %
Buffalos' drinking water	26 ± 2.5	3%	0.4%
Cleaning milking parlour	2.3 ± 0.1	0.3%	0.03%
Cooling system	1.1 ± 0.1	0.1%	0.02%
Cheese factory activities	20.5 ± 10.2	3%	0.3%
[a]Home consumption	0.7	0.1%	0.01%
Subtotal	*816 ± 285*	*100%*	*12%*
Grey water			
On-farm crop	1365 ± 573	69%	20%
Off-farm crop	614 ± 332	31%	9%
Subtotal	*1979 ± 566*	*100%*	*29%*
Total	*6820 ± 1490*		*100%*

All values presented in the table represent the mean ± standard deviation across the nine dairy farms investigated.
[a] The value is presented without a standard deviation because it is assumed to be the same for all dishwashers.

The green Wfc, accounting for 4025 ± 914 L/kg of mozzarella, was predominantly influenced by off-farm crop, which was responsible for approximately 52% of the total WF. On-farm crop water usage also played a significant role, representing 7% of the total WF.

For the blue Wfc (816 ± 285 L/kg of mozzarella), the most significant share came from off-farm feed water use, accounting for 61% of the blue Wfc and 7% of the total WF. On-farm crop water use constituted 33% of the blue Wfc. Other contributions to this fraction came from buffalo drinking water (~3%), cheese factory activities (~3%), cleaning of milking parlours (0.3%), cooling systems (0.1%), and home consumption (0.1%).

With regard to the grey Wfc (1979 ± 566 L/kg of mozzarella), the predominant source was on-farm crop water use, amounting to 69% of this fraction. Off-farm crop water uses contributed the remaining 31%.

For a comprehensive breakdown of the specific volumes and percentages of each Wfc refer to Tables 4 and 5. This tables offers an in-depth understanding of how various activities, from crop production to home consumption, contributed to the overall WF of buffalo mozzarella.

5.2. Home consumption

Analysis based on consumers' response pointed out no significant water usage, except in the case of dishwashing. It was reported predominantly that dishwashers were used for cleaning dishes. Therefore, for the estimation of water consumption in this activity, dishwashing was assumed to be conducted using a dishwasher, consuming approximately 13.3 L of water per cycle, as per Energy Star's data (https://www.energystar.gov/products/appliances/dishwashers/key_product_criteria, accessed on November 23, 2023). This assumption serves to quantify the water use during the final consumption phase of buffalo mozzarella.

5.3. Water footprints of various crops

The WF profiles of different crops associated with buffalo mozzarella production was also evaluated. Results presented in Fig. 2, highlighted the differences between crop type in terms of green, blue, and grey Wfc.

Corn silage showed total WF equal to 5752 m^3/ha. The composition

Table 5
Water footprint contributions by crop and feed type per kilogram of buffalo mozzarella.

Crop/Feed	kg [a]DM/kg Mozzarella	L water/kg mozzarella	Incidence on tot. WF
On-farm			
Corn silage	1.258	438	6.4%
Sorghum silage	0.431	138	2.0%
Triticale silage	0.581	206	3.0%
Hay in rotation	0.548	542	7.9%
Hay non-rotation	0.318	811	11.9%
Subtotal	*3.136*	*2134*	*31.3%*
Off-farm			
Corn flour	0.724	762	11.2%
Soy flour	0.409	867	12.7%
Barley flour and roots	0.483	578	8.5%
Wheat bran	0.092	142	2.1%
Field bean	0.598	1014	14.9%
Cotton	0.203	227	3.3%
Fat	0.033	31	0.5%
Flax	0.155	174	2.6%
Spent grains	0.936	234	3.4%
Concentrate	0.380	607	8.9%
Subtotal	*4.013*	*4636*	*68%*
Total	*7.149*	*6770*	*99.3%*

[a] Dry matter (DM) is standardised considering 35% of DM for silages and 88% of DM for hay.

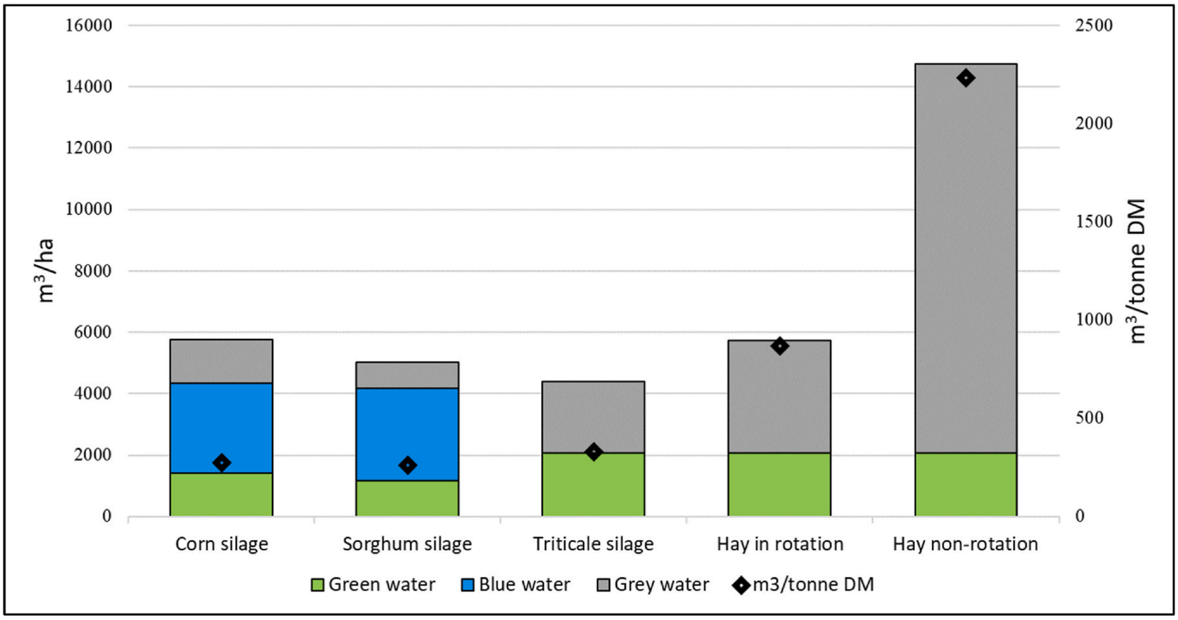


Fig. 2. Comparison of water fractions (green, blue, and grey) per hectare and per tonne of various on-farm crop used by the nine investigated farms involved in buffalo mozzarella production

The figure provides a comparison of water footprints (WF) categorized by green, blue, and grey water fractions (Wfc) usage for various crop types utilized in buffalo mozzarella production. The left y-axis indicates the Wfc for each crop type per unit of area. The right y-axis reflects the WF required to produce one tonne of standardised crop dry matter (DM) considering 35% of DM for silages and 88% of DM for hay. Stacked bars represent the partitioning of the total WF into green, blue, and grey Wfc for each crop type. Diamonds overlaying the bars denote the specific WF per tonne standardised crop DM..

of WF was 24.7%, 50.5% and 24.8% of green, blue and a grey Wfc, respectively. The WF per tonne of corn silage was 96 m^3, and when considering its standardised DM content, the WF was 274 m^3 per tonne.

Sorghum silage showed a total WF of 5017 m^3/ha. The green, blue, and grey Wfc contributed for 23.5%, 59.7%, and 16.8%, respectively. The WF per tonne of sorghum silage was 91 m^3, and when considering its standardised DM content, the WF was 261 m^3 per tonne.

The WF profile of triticale silage does not present blue Wfc. The total WF of 4388 m^3/ha consisted of 47.4% green and 52.6% grey Wfc. The WF per tonne of sorghum silage was 115 m^3, and when considering its standardised DM matter content, the WF was 330 m^3 per tonne.

This study examined also the WF of hay crops, specifically focusing on the difference between hay included in a crop rotation and hay not included in rotation. The total WF for hay in rotation was 5730 m^3/ha, primarily made up of green (36.3%) and grey Wfc (63.7%). Notably, as no irrigation was applied to this crop, no blue Wfc was detected. This crop exhibited a WF of 868 m^3 per tonne of standardised DM.

Finally, hay not in rotation presented a high total WF of 14,734 m^3/ha. The contributions to this WF were significantly skewed, with a minor green Wfc of 14.1% and a dominant grey Wfc accounting for 85.9%. The WF for this crop was also the highest among all crops, reaching 2232 m^3 per tonne of standardised DM.

Table 5 summarizes the WF contributions for producing 1 kg of buffalo mozzarella, highlighting the significant on-farm and off-farm

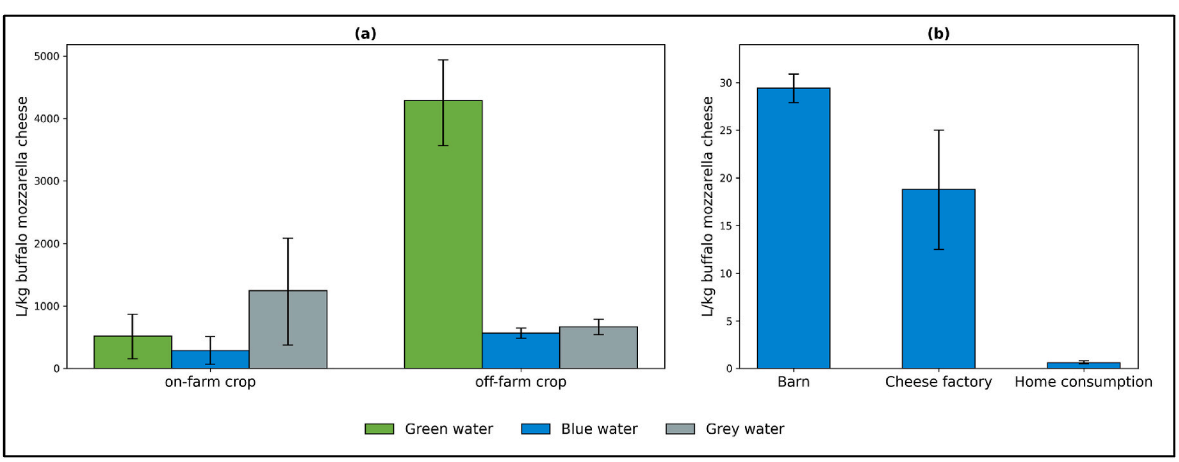


Fig. 3. Uncertainty distribution in green, blue and grey water fractions across production and consumption phases of buffalo mozzarella cheese

(a) Uncertainty distribution of the water footprint (WF) for buffalo mozzarella cheese production, delineated by on-farm and off-farm crop water fractions (green, blue, and grey). (b) Breakdown of WF by production stage, including the barn, cheese factory, and home consumption. The bars represent median WF estimates, and the error bars indicate the 25th and 75th percentiles. These estimations are derived through bootstrap technique with Monte Carlo simulations accounting for variations in climatic conditions, differences in feed rations provided to livestock, variability in milk and meat production across different farms, as well as the variability in water used for livestock drinking, barn' cooling systems, cleaning of milking parlours, cheese factories, and home consumption water use..

sources. On-farm, non-rotation hay was the largest contributor, accounting for 11.9% of the total WF. Off-farm, field beans lead with a 14.9% contribution, followed by soy flour at 12.7%.

5.4. Uncertainty results

Fig. 3 illustrates the uncertainty associated with the green, blue, and grey Wfc across various phases in the production and consumption of buffalo mozzarella cheese. The error bars throughout the graph represent the interquartile range, indicating the spread from the 25th to the 75th percentile, thereby quantifying the extent of uncertainty associated with each Wfc in the corresponding production and consumption phases.

The on-farm crop production phase is marked by substantial variability, particularly in the grey Wfc, which shows the highest degree of uncertainty. The blue and grey Wfc exhibit a narrower, although consistent, range of uncertainty. Notably, off-farm crop production is characterized by a significant uncertainty in the green Wfc.

As regards to the barn phase, there is a distinct degree of uncertainty in the blue Wfc, which is notable though less than that observed in the CFs. The final stage, home consumption, displays the least variability in blue Wfc estimates, suggesting a more predictable pattern of water usage.

6. Discussion

The study focuses on the WF associated with buffalo mozzarella production, highlighting that feed production is the principal component, as already reported in previous studies [3,18,21,41]. This reveals the complexity of managing water in agriculture, particularly through the analysis of WF profiles of crops used in production. The significant role of green Wfc, primarily from rainwater transpired or evaporated by crops, is underscored, aligning with findings of other authors [3,21,33,42]. This calls for a deep analysis of green water's role in sustainability and environmental evaluations.

In addressing green water utilization, it is advisable for farmers to prioritize the optimization of rainfall management, which in turn can decrease the need for irrigation [3]. An effective approach is to minimize the green Wfc by converting unproductive soil evaporation into beneficial plant transpiration that supports biomass expansion [43]. This can be accomplished by managing crop residues to ensure that the soil maintains its infiltration and water retention capacity, especially through practices such as conservation tillage or minimum tillage. Employing either organic or artificial mulch and integrating cover crops can strengthen plant growth's water efficiency. This may be achieved by reducing soil evaporation and encouraging plant transpiration [44,45].

The green Wfc is a critical and debated aspect in water accounting [46]. Indeed, some authors highlighted that in the absence of agricultural crops, those areas might instead be forested or shrublands, naturally utilizing more green water due to their larger biomass and higher rates of evapotranspiration [47,48]. This observation raises concerns that current methodologies might not fully capture the distinct water dynamics in natural ecosystems, leading to a potentially unfair assessment of the agricultural WF [14,49]. On the other hand, Hoekstra [50] emphasized that fully understanding the role of green Wfc requires more than just comparing its usage in pre- and post-agricultural land transformations, such as the shift from forests to farmlands. He argued that a comprehensive assessment should delve into the broader context and implications of green water use, not just its net change. This perspective highlights the importance of evaluating green water usage in a more holistic manner, considering factors beyond simple land use alterations. For instance, a crop with high green water usage but low yield demonstrates poor green water productivity, leading to a larger green Wfc per unit of production. Thus, when evaluating the WF of different farming methodologies, it is important to include their green water productivity, reflecting how efficiently rainwater is used to generate yield.

The analysis of blue Wfc in buffalo mozzarella production reveals a significant disparity, with off-farm feed water use as a key factor, accounting for 61% of the total blue Wfc. This highlights the substantial impact of external feed production on water resources in mozzarella production. Additionally, the contribution of on-farm crop water use (33%), buffalo drinking water, cheese factory operations, and household consumption, underscores the influence of localized agricultural practices on the overall WF. Such insights emphasize the impact of local practices on the overall WF of mozzarella production.

This distribution accentuates the multi-faceted nature of blue water sources in dairy production. This observation agrees with findings from other authors [21,41,51,52], underscoring the need for diverse water management strategies for dairy products due to the several water-consuming processes. To address this segmented consumption, a holistic approach to sustainability is paramount, focusing on optimizing water efficiency in each segment. Given that the blue Wfc includes 12% of mozzarella cheese's total WF, there is a potential for reducing this by refining water management practices throughout the production cycle.

Starting with fields, strategies such as deficit irrigation, where crops are subjected to specific periods of water stress, have proven valuable in amplifying irrigation efficiency [53,54]. Additionally, it has been reported that sprinkler irrigation systems are more efficient in water usage compared to surface irrigation methods [53,54]. Likewise, adopting drip irrigation and both organic and synthetic mulching techniques offer further avenues for reducing water and heat loss from soil [44].

From the volumetric perspective, the result obtained in this study are within the range of volumes per hectare reported by others [3,55]. Corn and sorghum silage, differ slightly in their individual WF profiles, which was also found by Ibidhi and Ben Salem [3]. As reported by Bhattarai et al. [56] sorghum's WF per tonne is slightly lower than corn's. This might imply that sorghum, from a water efficiency perspective, might be a more sustainable choice. However, when comparing these crops, nutritional factors must also be considered [57]. Indeed, sorghum generally produces less DM per hectare than corn and offers lower protein and starch content and lower digestibility, which could affect feed quality. Additionally, while some types of sorghum might contain tannins, a family of anti-nutritional factors that can impact its use as livestock feed [58], it is important to notice that recent varieties of forage sorghum have been developed to mitigate this issue significantly. Therefore, in buffalo mozzarella production, the use of specific varieties of sorghum may represent a valuable alternative to maize.

Within dairy farms, the use of cooling systems that incorporate both water-based mechanisms and ventilation is crucial for maintaining the well-being of buffaloes. The effectiveness of cooling system lies in its ability to prevent significant drops in milk yield during heat stress conditions. Improving milk yield during hot seasons, results in a more efficient water usage when considering the total water consumed per unit of milk produced [21]. Also, for the CFs activities, from the volumetric perspective, the value obtained in this study are within the range (10–47 of litres per kg of mozzarella) reported by others [16,59]. For CFs, strategies that focus on optimizing water flow rate, advanced process controls, reducing water use in cleaning processes, and approving water reuse and recycling can contribute substantially to the reduction of blue Wfc [60]. This encompasses the treatment and subsequent reuse of wastewater for non-potable applications, including the cleaning of floors, thus presenting a pragmatic solution for conserving water resources.

The majority of the grey Wfc was attributed to on-farm crop cultivation practices, with the rest resulting from off-farm feed water use. As sustainability has become a focal point in the dairy sector, efforts to address water quality both on- and off-the farm are pivotal for enhancing sustainable mozzarella production. As also observed by Ibidhi and Ben Salem [3], the absence of the blue Wfc in triticale silage points to its reliance on natural precipitation rather than irrigation. This characteristic indicates its potential as a resilient crop. The same pattern applies to hay mixtures. However, the high grey Wfc draws attention to environmental challenges potentially associated with nutrient runoff or pollution.

Soil texture plays a critical role in this process; coarse-textured soils like sandy soils are more susceptible to nitrate leaching due to their high permeability, which allows for quicker movement of water and dissolved nitrates compared to finer-textured soils such as clay. In contrast, clay soils, with their smaller particle sizes and lower permeability, more effectively retain water and nutrients, thus reducing leaching potential [61]. Additionally, the mineralization of organic nitrogen can lead to nitrogen loss through leaching, especially during fallow periods post-harvest [62]. In this regard, the introduction of cover crops can decrease nitrate leaching risk, especially during vulnerable periods like fallow [63]. When considering fertilizer types on a larger scale, organic fertilizers are usually associated with 30–40% lower leaching losses compared to inorganic fertilizers [64]. However, certain studies have reported up to 20% greater leaching for organic versus synthetic fertilizers [65]. Despite this, the differences in leaching rates between organic and synthetic fertilizers tend to be minimal [66]. The tillage system also influences nitrate leaching; the impact of no-tillage practices on nitrate leaching remains contentious, with studies reporting both higher and lower leaching losses under no-tillage compared to conventional tillage [67].

The influence of the grey Wfc, attributed to nutrient leaching into groundwater and runoff into streams, on dairy products has also been documented by other authors [3,21,33,42]. Such leaching is predominantly observed in high-intensity agricultural systems, where the application of these nutrients could exceed plant uptake [68] or the specific needs of plants at various phenological stages. Furthermore, soil water movement can aggravate this issue, causing nutrients to leach into groundwater or undergo surface runoff. Noticeably, nitrates are particularly susceptible to leaching into the subsoil following extensive irrigation or heavy rainfall events [69].

To contrast this, improved water management techniques, like irrigation specifically tailored to crop needs, are vital in reducing nutrient leaching. Additionally, optimizing fertilizer application is essential. Combining both strategies not only minimizes nutrient leaching but also offers advantages to farmers, creating a balanced solution. Indeed, this synergistic approach leads to improved crop yields and enhanced nitrogen use efficiency, thus creating a balanced and sustainable agricultural solution [70]. Furthermore, the adoption of cover crops has proven effective in limiting leaching [71]. In particular, the rotation of alfalfa with crops like corn has been shown to effectively reduce nitrate leaching, offering a practical and environmentally friendly approach to crop management [72].

Considering that phosphorus leaching is minimal due to its low solubility in soil [73], the grey Wfc is largely influenced by N fertilizers [74]. In this study, nitrate leaching was the focus when calculating the grey Wfc. The DNDC model, well-validated and aligned with measurements of N_2O, NH_3, NO_3 leaching, and yields in temperate systems [75], estimated N leaching per hectare to be between 32 and 71 kg. The weighted average annual leaching factor of N applied was 24.5% for the farms in the present study and was slightly below the 27.3% national rate reported by the Italian Institute for Environmental Protection and Research [76].

The substantial grey Wfc recorded for the non-rotational hay mixture crop hectares investigated in this study was attributed to those areas remaining fallow for part of the year, during which no crop uptakes the residual N. Meanwhile, the grey Wfc observed for triticale silage can primarily be attributed to the more significant rainfall events occurring during the autumn-spring period, which coincides with the sowing and harvesting period of this crop. Indeed, fertilizer dissolved in precipitation water may quickly move through soil macropores to depths below the rooting zone, and intensive precipitation leads to large amounts of nitrate being leached over winter [67].

Integrating cover crops in place of fallow periods can significantly reduce nitrate leaching from croplands [77,78], underscoring an area for potential environmental improvement. Millet, for example, is a heat and drought-resistant fodder crop that can be harvested as hay, green chop, or silage and has shown its potential as an efficient feed option for dairy cattle and buffaloes [79,80]. In regions like Central Italy, where summer droughts can limit crop choices, replacing fallow periods with drought-resistant crops like millet that could effectively utilize residual N, might reduce nitrate leaching and thus the grey Wfc.

In the field of agriculture, quantifying WF is complex due to the absence of a universally accepted methodology. The two main approaches are the Water Footprint Network (WFN) [10] and the ISO 14046 standard [11]. WFN focuses on water usage in supply chains, aiming for efficient resource management. In contrast, ISO 14046, based on ISO 14044's life cycle assessment, addresses environmental impacts of water scarcity and pollution [13,15,50,81]. The different focuses and lack of a specific computational method in these approaches make results from different studies hard to compare. Lack of a standardized approach has thus led to various assessment techniques, which complicate comparisons among studies. Literature data from Atzori et al. [49], Manzardo et al. [82], Bai et al. [83], De Girolamo et al. [37], Fridman et al. [84], and Jamshidi et al. [85] testify such lack of standardization. This diverse range of methods underlines the need for a more unified calculation model for WF in agriculture, to enable effective comparison and support sustainable water management. For instance, a study conducted in Brazil by Alves et al. [16] utilized SimaPro v.8.5 software in conjunction with the ReCiPe2008 method, specifically employing the Water Depletion (WD) approach, estimated a water usage of approximately 0.113 m^3 per kilogram of buffalo mozzarella cheese. Another study from Italy by Oliveira et al. [17], focusing on buffalo mozzarella cheese from the Campania region, applied the ReCiPe2016 method with SimaPro v.9.0 software and reported a Water Consumption Potential (WCP) ranging between 0.03 and 0.1 m^3 per kilogram of mozzarella. Such discrepancies were found also in studies concerning cattle mozzarella cheese, even when the studies share parameters like milk origin, cattle breed, and the use of the same WD method (ReCiPe2008 Midpoint method). Reported values vary significantly, ranging from 0.448 to 0.655 m^3 [18] to 4.93–9.38 m^3 [19] per kilogram of cattle mozzarella cheese. Such methodological inconsistencies highlight the critical need for the standardization of WF assessments. Establishing a unified approach would allow for more precise comparisons and for a deeper understanding of the environmental impacts of dairy products. The development of comprehensive guidelines tailored to the unique aspects of livestock products would greatly enhance the clarity and reliability of WF studies in the dairy sector.

6.1. Limit of the study

The significance of incorporating uncertainty analysis into WF assessments is well-recognized for its role in understanding water use and pollution levels in agriculture [38,39]. Despite this, the practical application of such analyses is often limited, and the gap between modelled estimates and actual water usage and pollution is a notable challenge [37]. Real-world data, with its varied distributions, presents difficulties in defining clear characteristics, making conventional analysis methods less effective.

Models, while based on established methodologies and aiming to mirror real agricultural scenarios, may fall short in capturing the detailed, local conditions of farms due to the lack of direct data, potentially skewing WF outcomes [37]. The situation is further complicated by the diversity of farming practices within even similar areas. Differences in soil, irrigation, crop rotation, and farm management can significantly influence the green, blue, and grey Wfc. In this study, the uncertainties identified in the WF of on-farm crops were influenced not only by potential inaccuracies in crop modelling but also by significant variations in cultivated areas and the diversity of crop rotations practiced on the farms. This inter-farm variability affects the

WF both directly through water consumption and indirectly via the types and quantities of off-farm feed used. The employment of secondary data for off-farm feed and the reliance on global averages provide by Mekonnen and Hoekstra [30,31] further compound these uncertainties [21].

According to De Girolamo et al. [37] and D'Ambrosio et al. [38], the complexity intrinsic in WF assessments necessitates comprehensive uncertainty analysis. Simulation techniques, offering the ability to generate a spectrum of possible outcomes, emerge as a promising solution. Such simulations facilitate the determination of key uncertainty metrics, including SD and interquartile ranges, relying on a blend of bootstrap and Monte Carlo methods. Despite the intensive computational demands, this detailed approach to uncertainty analysis is crucial. The significant uncertainty highlighted in our research underscores the need for a thorough examination of these aspects to improve the accuracy and applicability of WF assessments within the agricultural sector.

7. Conclusion

In this study, the WF of buffalo mozzarella production in central Italy was analysed, utilizing the WFN methodology. The significant impact of the green Wfc was revealed, with off-farm feed water usage accounting for the largest share of the overall WF. Although off-farm feed remains a major contributor, the emphasis of on-farm impacts provided crucial insights on hotspots of water consumption within the mozzarella supply chain.

The study reveals that the blue Wfc, though more evenly distributed, represents a considerable part of the total WF, significantly influenced by off-farm feed water use. These insights need a multifaceted approach to water management that accommodates the various water-consuming processes in dairy production.

Attention was also drawn to the grey Wfc, predominantly impacted by on-farm crop cultivation. The study highlighted the critical role of nutrient management in mitigating environmental impacts, particularly focusing on nutrient leaching. The study, while identifying key water consumption hotspots, cautiously suggests that integrating sustainable practices such as cover crops and efficient irrigation techniques may effectively reduce grey water impacts and enhance environmental sustainability in agriculture.

Considering the critical insights gained from this study, it becomes evident that future research in WF assessments, particularly within the dairy industry, must prioritize increasing accuracy. To achieve this heightened level of accuracy, future studies should aim to integrate more granular, farm-level data, enabling a closer examination of the specific water use practices. By leveraging technology and data analytics, precision livestock farming can help validate and refine WF models, ensuring more accurate assessments.

Overall, this study contributed to an in-depth understanding of the WF of dairy production, especially emphasizing the significance of on-farm practices. It underscores the necessity for a holistic approach to water management that considers both on-farm and off-farm activities. The findings of this study offer valuable insights for the dairy industry and policymakers, advocating for sustainable practices that can mitigate the WF while supporting the economic sustainability of the sector.

Funding

This research was carried out in the framework of the project "TECBUFALA" (Project Code POR A0375E0184 – PROT. A0375-2020-36613) and supported by the POR FESR LAZIO 2014–2020 (grant number J85F20000570005) and co-supported by the European Union Next-GenerationEU (grant number J83C22000830005) within the "National Research Centre for Agricultural Technologies" research programme. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

CRediT authorship contribution statement

Giampiero Grossi: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Umberto Bernabucci:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Chiara Rossi:** Software, Methodology, Data curation. **Francesco Cesarini:** Software, Methodology, Data curation. **Nicola Lacetera:** Writing – review & editing, Supervision, Resources, Project administration. **Chiara Evangelista:** Data curation. **Giovanni Turriziani:** Resources. **Andrea Vitali:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors want to thank all the buffalo farmers, the cheese manufacturers and the consumers involved in this research for the support in providing essential information through the surveys.

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