BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Achieving net zero dairy farming

Edited by Emeritus Professor John Webster
University of Bristol, UK

E-CHAPTER FROM THIS BOOK

burleigh dodds
SCIENCE PUBLISHING

Advances in measuring the water footprint of dairy farming

António Cardoso Monteiro, Polytechnic Institute of Viseu, Portugal; and Özdal Gökdal, Aydın Adnan Menderes University, Turkey

1 Introduction
2 The water footprint concept
3 Water footprint assessment
4 Water management technologies
5 Case studies
6 Lessons from case studies
7 Conclusion
8 Acknowledgements
9 Where to look for further information
10 References

1 Introduction

Water is crucial on a dairy farm. It is essential for crop production (where crops are grown, e.g. for feed), animal consumption, cow comfort through water-based cooling, milk cooling, sanitation operations (such as maintaining animal hygiene and facility cleaning) and waste collection and transport (Robinson et al., 2016; Naranjo et al., 2020; Palhares et al., 2020). This requirement for water in milk production can lead to increased pressure to regulate and monitor water use, which creates significant challenges – especially financial – for farmers (Palhares et al., 2020).

There are currently studies that estimate water consumption in ruminant production systems; however, most are based solely on direct water use (Murphy et al., 2017; Palhares et al., 2020; Al-Bahouh et al., 2021). However, water consumption in livestock production should not be considered in isolation in calculating a water footprint (WF); it must include water consumption by others, e.g. industry, services and people, taking into account the available

http://dx.doi.org/10.19103/AS.2025.0157.07
© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

Chapter taken from: Webster J. (ed.), *Achieving net zero dairy farming*, pp. 75–100,
Burleigh Dodds Science Publishing, Cambridge, UK, 2026, (ISBN: 978 1 83545 018 5; www.bdspublishing.com)

water resources and their needs (Hoekstra & Chapagain, 2007; Hoekstra, 2017; Mekonnen & Hoekstra, 2010; Zhang et al., 2013).

Given increasing demand from population growth, agriculture is responsible for approximately 90% of freshwater consumption, of which 30% is used for livestock production (Mekonnen & Hoekstra, 2012; Zhang et al., 2013). Climate change impacts, including temperature increases, extreme meteorological phenomena and disturbances in ecosystems, are exerting more pressure on freshwater resources (Drastig et al., 2010).

Adaptation strategies for water consumption in agriculture seek to increase water use efficiency (WUE), e.g. through changes in agronomic practices, crop selection and optimization of dairy breeds. These strategies may include advances in feed production techniques, adoption of modern irrigation methods and enhancement of livestock system productivity. Changes in crop management practices – such as adjusting sowing dates and conserving soil moisture – can significantly increase water efficiency (Drastig et al., 2010; Monteiro et al., 2023).

This chapter aims to evaluate the findings from recent research and case studies. It focuses on the latest developments in measuring the WF of dairy farming, highlighting some strategies for optimizing water use and addressing sustainability challenges in the industry.

2 The water footprint concept

The WF concept, which was introduced by Hoekstra (Hoekstra, 2003) and later developed by Hoekstra and Chapagain (Hoekstra & Chapagain, 2008), links human consumption to global water resources and offers a comprehensive assessment of water consumption and its environmental impact (Drastig et al., 2010; Romaguera et al., 2010).

The WF concept offers a differentiated approach to understanding water use, addressing both water consumption and its impact on water quantity and quality. There are two globally accepted WF concepts (Palhares et al., 2020). These are the Water Footprint Standard (Hoekstra et al., 2011; Hoekstra, 2017) and life cycle assessment (LCA) (Drastig et al., 2010; Palhares et al., 2020). The concept of the Water Footprint Standard was used to evaluate the WF of dairy milk in a cradle-to-farm gate perspective which categorizes water use into (Hoekstra et al., 2011):

- Green water: Rainwater used for irrigation or other purposes.
- Blue water: Groundwater or surface water extraction.
- Grey water: Wastewater from household activities (suitable for irrigation).

The WF is a comprehensive metric for assessing the use of freshwater resources and goes beyond the conventional metrics that focus exclusively on water

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

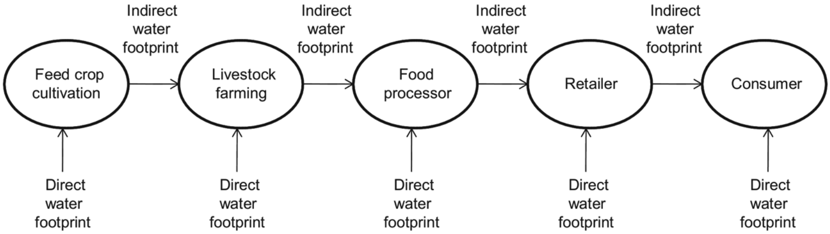

Figure 1 The direct and indirect water footprint in each stage of the supply chain of an animal product product. Source: Adapted from: Hoekstra et al. (2011).

abstraction. The WF is defined as the total volume of freshwater used in the production of a given product. This measurement encompasses calculations derived from primary data on direct and indirect water consumption, the nitrogen load of effluents and processes related to feed and milk production (Fig. 1). A necessary distinction exists between direct and indirect WF in dairy systems, where direct WF includes on-farm water usage, and indirect WF captures off-farm water usage for feed production (Bronts et al., 2023). Consequently, the WF of a dairy cow comprises the indirect WF of feed production and the direct WF of drinking and service water components (Chapagain & Hoekstra, 2003, 2004; Mekonnen & Hoekstra, 2012).

The concept of WF is closely related to the concept of virtual water, which refers to the volume of water required to produce a good or service (Hoekstra & Chapagain, 2007). This emphasizes the flow of 'virtual water' through international trade, which can be calculated for various entities, including goods, services, activities, companies, organizations, individuals and communities (Chapagain & Hoekstra, 2003, 2004; Hoekstra, 2003; Hoekstra & Chapagain, 2007, 2008; Mekonnen & Hoekstra, 2012). Agricultural commodities incorporate significant amounts of green, blue and grey water. Understanding these flows allows countries and industries to assess their indirect water use and manage resources more effectively (Drastig et al., 2010; Hoekstra et al., 2011).

LCA integrates environmental impacts throughout the production chain, ranging anywhere from on-farm processes to retail. Although LCA has been used to assess greenhouse gas emissions and other impacts, its application to water use in dairy farming remains limited. Studies suggest that most environmental impacts occur during the farming phase, including crop production, effluent management and the use of drinking water (Drastig et al., 2010; Høgaas Eide, 2002).

3 Water footprint assessment

Dairy farming has come under public scrutiny due to concerns about both animal welfare and environmental impact. In response, the dairy industry is

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

attempting to cope with climate change by enhancing animal adaptability, improving feeding efficiency, adopting less water-intensive cultivation practices (for feed crops) and increasing water reuse.

The WF of a product consists of the total amount of water consumed (which cannot then be re-used without further treatment) by that product. For instance, the WF of 1 L of milk has been estimated at approximately 1020 L of water, which considers water used for feed production, drinking water and servicing (Mekonnen & Hoekstra, 2012). Water use can be classified into two categories: consumptive and non-consumptive use. Consumptive use involves removing water from its natural source, namely transforming it from liquid to vapour, thus reducing its availability in terms of place and time. Non-consumptive use (Fig. 2) returns almost all the water to its source, although there may be some changes in the timing of its availability (Monteiro et al., 2023; Perry et al., 2023).

It is necessary to quantify water consumption on farms in order to manage water use and reduce consumption efficiently. This quantification can be done directly through monitors, such as water meters, or through estimates based on models or reference values (Cullens, 2011; Monteiro et al., 2023).

Early assessments of the WF of dairy production primarily focused on volumetric WFs, such as litres of water per litre of milk. However, these evaluations often lacked comprehensiveness. They did not account for the types of water used (blue, green, grey) or the specific water scarcity conditions in different regions, necessitating more nuanced approaches to fully capture environmental impacts. This highlights the need for a more nuanced approach that recognizes the environmental impacts of water consumption (Ridoutt et al., 2010). Research indicates that farms with high WUE require fewer resources (water and land) to produce the same amount of milk. Moreover, effective farm

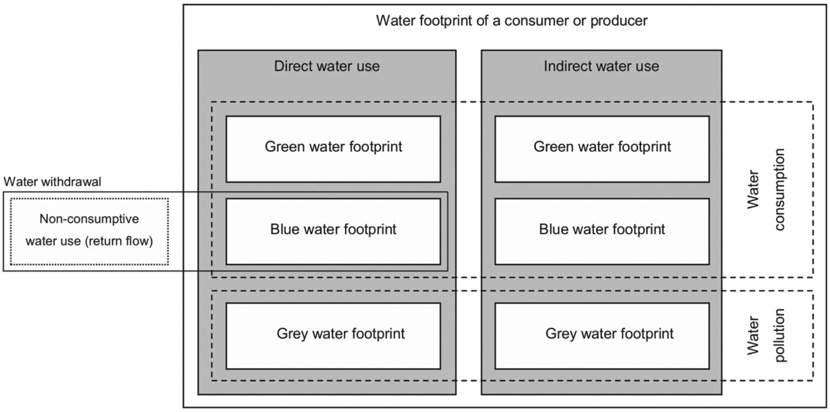

Figure 2 Representation of the components of a water footprint (Hoekstra et al., 2011).

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

management practices play a more significant role in WUE than the type of production system (Nagypál et al., 2020).

The WF of an animal can be calculated using the formula of Mekonnen & Hoekstra's (2012) (Equation 1):

$$WF_{(a,c,s)} = WF_{feed(a,c,s)} + WF_{drink(a,c,s)} + WF_{serv\,(a,c,s)} \tag{1}$$

where WF(a,c,s) represents the WF of an animal by category (a), in country (c) and in production system (s) considering feed, drinking water and service-water consumption.

Researchers use the total WF value per kilogram of fat- and protein-corrected milk (FPCM) to calculate the WF in a dairy farm (Grossi et al., 2022) (Fig. 3).

The FPCM, expressed in kilograms per year, can be determined using the International Dairy Federation (IDF, 2010) equation, which accounts for milk yield, fat and protein content (Equation 2) (Velarde-Guillén et al., 2023):

$$\begin{aligned} FPCM\left(\frac{kg}{year}\right) &= Milk\ yield\left(\frac{kg}{year}\right) \\ &\times\left(0.1226\times Milk\ fat(\%)+0.0776\times Milk\ protein(\%)+0.2534\right) \end{aligned} \tag{2}$$

Alternatively, Hodúr et al. (2022) used the FAO (2021) formula (Equation 3) to determine energy-corrected milk (FPCM):

$$\mathrm{FPCM} = \mathrm{Milk\ amount} \times \left(0.337 + 0.116 \times \mathrm{fat\%} + 0.06 \times \mathrm{protein\%}\right) \tag{3}$$

The WF of milk production can be estimated using the methodology set out by Mekonnen and Hoekstra (2012). According to this approach, the WF of milk production (M) is calculated by dividing the sum of WFs for feed (F), consumption (C) and services (S) by the annual FPCM, as shown in Equation 4:

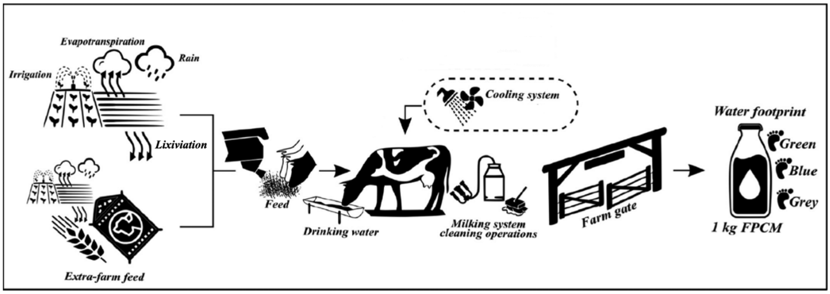

Figure 3 Overall milk water footprint. Source: Adapted from: Grossi et al. (2022). FPCM = Fat and Protein Corrected Milk.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

$$WF_M\left(\frac{m^3}{year}\right)=\frac{WF_F+WF_C+WF_S}{FPCM\left(\frac{\frac{kg}{farm}}{year}\right)} \tag{4}$$

The green, blue and grey WFs have been estimated by Mekonnen and Hoekstra (2012) for different countries, taking into account the type of production system (grazing, mixed and industrial) and differences in feed conversion efficiency, local climate, soil conditions and irrigation data. These authors estimated a total WF value of 1299 litres of water (Lw) per kg of FPCM, of which 91% was attributed to green water use, 5% to grey water use and 4% to blue water use (Shine et al., 2020a).

Green water was responsible for around 90% of the total WF. Feed production was the main driver of blue water use, accounting for up to 86% of total blue water use (Mekonnen & Hoekstra, 2010; Mekonnen & Hoekstra, 2012; Sultana et al., 2014; Shine et al., 2020a).

The WF of an animal related to the feed it consumes consists of two parts: the WF of the various feed ingredients and the water that is used to mix the feed. Feed footprint calculations include many variables and can be calculated by considering feed ingredients, volume and composition of feed, feed conversion efficiencies and estimation of feed composition (Mekonnen & Hoekstra, 2012).

Drinking water consumption (DWC) per lactating cow (litres/day) can be calculated using by equation set out by Meyer et al. (2004) (Equation 5):

$$\mathrm{DWC}=-26.12+1.516\left(t_{\mathrm{average}}\right)+1.29\left(m_{milk\ prod}\right)+0.058\left(m_{bodyweight}\right)+0.46\ m_{Na} \tag{5}$$

where t_{average} is the average temperature value, $m_{\mathrm{milk\ prod}}$ is the daily milk yield (kg/day), $m_{\mathrm{bodyweight}}$ is the bodyweight of animals (kg) and m_{Na} is the quantity of daily sodium intake (g/day).

The Grey Water Footprint (WF_{grey}) was estimated by Hodúr et al. (2022) based on Equation 6 as the water volume required to dilute pollutants in wastewater to acceptable levels:

$$WF_{process,gray}=\frac{L}{\left(c_{\max-c_{nat}}\right)}=\frac{\left(Effl\times c_{effl}-Abstr\times c_{act}\right)}{\left(c_{\max-c_{nat}}\right)} \tag{6}$$

where $WF_{\mathrm{process,grey}}$ is the grey WF of a process, it shows the pollutant load (mass/time), $c_{\max}$ is the maximum acceptable concentration of pollutant (mass/volume), c_{nat} is the natural concentration in the receiving water body (mass/

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

volume), Effl is the effluent volume/time, c_{effl} is the concentration of the pollutant in the effluent (mass/volume), Abstr is the water volume of the abstraction (volume/time), and c_{act} is the actual concentration of the intake water (mass/volume).

As mentioned in Section 2, assessment methods are approached through two different frameworks: the LCA and the Water Footprint Network (WFN) (Pfister et al., 2017; Bai et al., 2018).

The LCA protocol can be applied to analyse water consumption in raw milk production from cradle to farm gate, while also assessing the stress-weighted water scarcity footprint (WSF) and water scarcity productivity (WSP) (Liao & Su, 2019). The WSF is used to assess the potential environmental impacts of water scarcity resulting from an enterprise's activities within a specific area, such as a watershed or basin, without accounting for water quality (Bai et al., 2018) (Equation 7):

$$WSF = \sum_{i=0}^{n} = \left(\alpha SF, i \times Vi\right) \tag{7}$$

The WSF (m^3 H_2O-eq); Vi (m^3) represents freshwater consumption per unit time in position i; αSF,i is for characteristic factors corresponding to Vi; i is for different geographical location, e.g. watershed, region, nation, etc.

In their study, Liao and Su (2019) combined the WSI concept with WSP (Fig. 4).

Water productivity (WP) was defined as the physical quantity or economic value produced by a unit of water (Cai and Rosegrant, 2003). WP with the WSI as the equation can be combined by the formula used by (Liao and Su, 2019) (Equation 8):

$$\mathrm{WSP}\left(\mathrm{kg}/m^3\right) = P_i\left(\mathrm{kg}\right) / / \mathrm{WC}_i\left(\mathrm{m}^3\right)\mathrm{WSI}_i \tag{8}$$

WSP (kg/m^3) represents water scarcity productivity; P_i (kg) is for FPCM production per unit time in position; WC_i (m^3) is for water consumption per

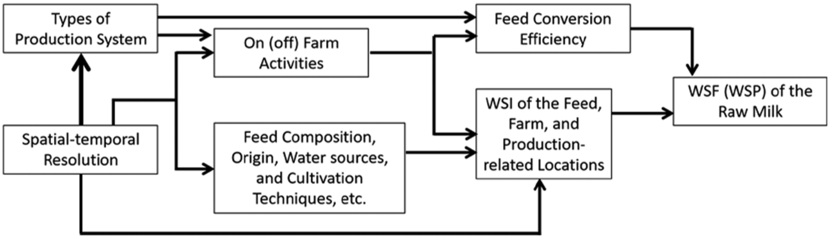

Figure 4 Factors that might affect the water scarcity footprint (WSF) or water scarcity productivity (WSP) of raw milk. Source: Adapted from: Liao and Su (2019).

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

unit time in position; WSI_i is for characteristic factors corresponding to P_i; i is for different geographical location (e.g. watershed, region, nation etc.). WSP can be increased by either increasing FPCM yield or reducing WC and maintaining the yield level or changing the production location to a low WSI region.

Some studies (Owusu-Sekyere et al., 2017; Ibidhi & Ben Salem, 2020) have associated the WF indicator with the economic water productivity (EWP) of livestock products, which is used to calculate the income generated per cubic meter of water used.

Studies have also used two other WF methods (Boulay et al., 2018; Higham et al., 2024):

- the WFN-based Blue Water Footprint Impact Index (WFIIblue) and
- the Available WAter REmaining (AWARE) water scarcity footprint (WFAWARE).

The Blue Water Footprint Impact Index (WFIIblue) is a method for assessing the water scarcity impact of blue water consumption during the production of a product. This method, based on the WFN approach, first calculates the consumptive blue water footprint (WFblue), which is the volume of blue water used per unit of product (m^3/kg of FPCM). In this method, WSblue becomes 1 when all the available blue water in the region has been consumed, significantly impacting the environmental water requirements. When WFIIblue is calculated in this way, it helps differentiate the water scarcity impacts of blue water consumption across regions with varying water resources and highlights areas where water scarcity might be more pronounced due to increased consumption (Higham et al., 2024).

The AWARE method is a recommended approach for assessing the impacts of water scarcity. It quantifies the relatively available water remaining per unit area after meeting the demands of humans and aquatic ecosystems. This method addresses the question: 'What is the potential to deprive another user (human or ecosystem) when consuming water in this area?'. The resulting characterization factor (CF) ranges from 0.1 to 100 and is used to calculate water scarcity footprints, as defined by the ISO standard. AWARE is based on the available water remaining in each watershed (measured relative to the global average) after accounting for human and ecosystem water requirements (Higham et al., 2024).

Waltner et al. (2023) quantified the total water footprint (WFanimal) of dairy cattle on a per-animal basis, focusing on climatic factors such as Temperature-Humidity Indices (THIs). The WFanimal was calculated as the sum of indirect water consumption (WFfeed) and direct water use for drinking (WFdrink) and servicing (WFserv). For crops such as maize, alfalfa hay and barley, green WFs were estimated using evapotranspiration (ET) and yield data.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

Water consumption by dairy cows can be influenced by various factors, such as dry matter intake, milk production, feed composition (dry matter, protein content) and climate. Water temperature also affects water consumption with higher intakes resulting from temperatures that are closer to body temperature (Meyer et al., 2004; Erina et al., 2013; Sultana et al., 2014; Golher et al., 2021; Salcedo et al., 2022).

Dry matter intake has an impact on the frequency and duration of water intake, with evidence that an increase in dry matter intake also increases water consumption. Production systems also have an impact on water use, with small-scale farms and those with lower production showing higher water consumption per unit of milk (Sultana et al., 2014).

Dairy cattle require approximately 80 litres of water/cow/day (ranging from 14 L/day to 171 L/day) for animal consumption, and if the volume of water for cleaning facilities, equipment and (in some cases) cooling the environmental temperature is added, the result could be a consumption of water use between 130 L/day/cow and 195 L/day/cow (Meyer et al., 2004; Nagypál et al., 2020; Naranjo et al., 2020; Grossi et al., 2022).

Modelling water use on dairy farms provides the advantage of being less expensive than installing metering equipment. Models can be developed to predict animal water intake, parlor water use and green and blue water requirements for milk production.

Models obtained by multiple linear regression use several variables, such as those related to farm area, milk production, herd size, concentrates, grass growth, imported feed and fresh water consumption measured on the farm (direct water) to predict green and blue water consumption (Higham et al., 2017; Shine et al., 2020a). The variables collected from the farm must be easily obtainable and collected on a large scale without the use of specialized equipment.

The use of machine learning or deep learning algorithms could contribute to the development of water consumption prediction on dairy farms, especially if there is a large amount of data collected in a standardized way and at an international level, establishing a global model for predicting water consumption on dairy farms (Higham et al., 2017; Shine et al., 2018, 2020a; Osaki et al., 2024).

4 Water management technologies

As can be seen, several factors can influence WF, and it is possible to control these factors to reduce the WF either directly or indirectly. Reducing the WF should be included in the initial planning of a farm to optimise the efficient use of water through the installation of equipment and the construction of facilities that consider the use of water, waste water treatment and irrigation systems.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

To minimise water losses from drinkers installed in facilities, it is essential to carefully select the type, number and location of these devices. In cattle housing, the use of constant-level drinkers is recommended to reduce water wastage over the use of valve drinkers. In addition, any drinker, whether a trough or a bowl, must allow each animal to consume water at a minimum rate of 10 L/min (Flaba et al., 2014).

Hydraulic waste dragging systems streamline floor cleaning operations but significantly increase effluent production. Water consumption in cleaning dairy cow facilities can be minimized by optimizing floor and equipment washing procedures. For instance, effective strategies to clean efficiently and quickly include using hoses with flow-controlled nozzles or employing high-pressure systems (USDA, 2012). Additionally, incorporating V-shaped floors with a 3% slope and central drains or perforated rough flooring with a 0.5% perforation for urine removal or separation further reduces water usage by enabling the use of mechanical dragging systems (Monteiro et al., 2023).

Pre-cooling milk with water using a plate cooler can reduce the energy required to cool milk by up to 50%, but it is important to consider the financial and environmental impact of the water use (Shine et al., 2020b).

Many dairy farmers recycle the water used to pre-cool the milk for farm washing or animal drinking, provided it is potable. Some producers pre-cool their milk without recycling the water, while others don't use a milk pre-cooling strategy at all. Consequently, the milk pre-cooling method chosen will affect the total water and energy consumption associated with cooling the milk, depending on factors such as the water/milk ratio of the plate cooler, the type of wash hose used, the size of the parlour, the size of the plate cooler and the volume of the wash water tank (Shine et al., 2020a).

Technologies such as rainwater harvesting and wastewater treatment have been shown to reduce reliance on groundwater and minimise environmental impact (Willers et al., 1999; Nagypál et al., 2020).

Effluent management technologies include physical-chemical separation of solids, anaerobic or aerobic treatment, and vegetative treatment. Solids can be separated using press or centrifuge equipment, with or without chemical agents. Anaerobic treatment can be done using digesters or anaerobic lagoons, while aerobic treatment can be performed in lagoons or tanks with various aeration methods. These treatment systems for dairy wastewater offer dual benefits of water reuse and pollution mitigation. For example, aerobic fermentation has been used to convert liquid waste into organic soil conditioners, reducing nutrient run-off and pollution risks (Harlia et al., 2024). Likewise, woodchip filters have been effective in removing organic matter and nutrients, making effluent suitable for reuse in farm operations (Ruane et al., 2011). Reverse osmosis technology in dairy plants has similarly demonstrated substantial reductions in wastewater volume and enhanced water reuse

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

efficiency (Vourch et al., 2008). Vegetative treatment involves using rooted plants in constructed wetlands or floating aquatic plants in lagoons (Burton & Turner, 2003; Sommer et al., 2013; USDA, 2012).

Advances in irrigation technology contributed to more sustainable irrigation practices, such as automated precision irrigation and sensor-based monitoring, which have significantly reduced water usage on dairy farms by optimizing water use in dairy pastures, enhancing productivity while reducing water waste (Jordan et al., 2021; Monteiro et al., 2021; Vallejo-Gómez et al., 2023). For example, sensor-based systems and crop models optimize irrigation efficiency by addressing spatial and temporal water demand variability (Hills et al., 2016).

Remote sensing provides significant advantages in efficient irrigation management. Techniques such as using satellite imagery (e.g. Landsat) to estimate ET and map water depth enable the development of intelligent systems that generate prescription maps for variable rate irrigation, thereby optimizing water application (Farg et al., 2017; Mendes et al., 2019). Thermal and multispectral images obtained by unmanned aerial vehicles or drones also help identify different irrigation needs that allow improved irrigation management (Cozzolino, 2017).

Wireless sensor technologies have advanced, providing low-cost, energy-efficient smart sensors to monitor soil moisture and incorporate meteorological data. Wireless sensor networks (WSNs) consist of spatially distributed devices connected wirelessly, often using technologies such as ZigBee, LoRa and GPRS for irrigation control due to their range, cost, energy efficiency and reliability. These sensors measure humidity, temperature and soil moisture, automate irrigation, enable real-time control and reduce water consumption to increase WUE (Aqeel-Ur-Rehman et al., 2014; Jawad et al., 2017; Ojha et al., 2015).

The integration of technological innovations can lead to significant improvements in both environmental sustainability and farm productivity. While some of these technologies resulted in increased water and energy consumption, the overall benefits in terms of milk yield, quality and animal health can be outweighed by additional resource usage. There is potential for precision livestock farming (PLF) and big data and artificial intelligence (AI) technologies to reduce the WF of dairy farming in the future (Lovarelli et al., 2024; Neethirajan, 2024). For example, the integration of PLF systems, such as sprinklers that activate automatically based on cow presence, demonstrated significant decrease in water consumption with the potential to reduce consumption from water sprinklers up to 25% (Lovarelli et al., 2024).

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

5 Case studies

Water is a critical resource in dairy farming that is utilized at every stage of production from feed cultivation to animal drinking and facility cleaning. As freshwater availability becomes increasingly constrained due to climate change and population growth, managing the WF in dairy systems has become crucial. This section presents several case studies from diverse geographies, methodologies and innovative solutions that optimize water use and improve sustainability in dairy farming.

One of the studies on WF in dairy farming was conducted by Palhares and Pezzopane (2015), who evaluated the WF of conventional and organic dairy production systems in Brazil. Their study revealed that green water was the largest contributor to the total WF for both systems, and accounted for 39–57% in conventional systems and 32–59% in organic systems. Irrigation water dominated blue water use, with 95% in conventional and 96% in organic systems. Grey WF, calculated using phosphorus as an element, were 1.5 and 1.9 times higher for conventional and organic, respectively. The blue water scarcity index was slightly higher for organic systems (0.13) than for conventional (0.11). The study concluded that WF values alone do not fully capture the environmental impacts, as these depend on regional water availability and production factors. The study emphasized the importance of improving irrigation practices and optimizing green and blue water use to enhance water efficiency. Despite being in high rainfall regions, both systems faced green water scarcity with an index of 1.1. The study identified key management strategies to enhance WUE such as improving irrigation practices, implementing best management practices to optimize green and blue water use and reducing grey water emissions through better nutrient and wastewater management.

Nutritional interventions also play a crucial role in reducing WF. Palhares et al. (2019) evaluated dietary strategies in Brazilian dairy systems and found that adjusting protein levels in feed from 23% to 14.5% reduced the total WF by 10%, with green water consumption accounting for most of the savings. This study highlights the potential of feed optimization in improving WUE.

Liao & Su (2019) explored the environmental impacts of milk production in Taiwan through a LCA approach. Their analysis incorporated the WSF and WSP across five farms. Results revealed significant variability in water use, with WSF ranging from 2.2 H_2Oeq/kg to 44.8 H_2Oeq/kg FPCM, depending on regional water stress levels. Farms with lower stress levels achieved a higher WSP of 0.749 kg FPCM/m^3 water, underscoring the importance of targeting water scarcity hotspots in dairy farming. The study applied the methodology developed by Ridoutt et al. (2010), which focuses on assessing water scarcity by prioritizing blue water consumption and its availability for human and environmental needs. This method is distinguished between blue, green and

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

grey water, highlighting that only blue water directly contributes to scarcity, while green water is linked to land use impacts and grey water reflects water quality degradation.

In arid regions like Kuwait, Al-Bahouh et al. (2020) assessed the blue and grey WFs of confined dairy farms, finding significant seasonal variations. The blue WF was higher during the summer (54.5 L/kg FPCM) compared to winter (19.2 L/kg FPCM), while the grey WF, influenced by phosphate concentration in effluent, averaged 23.0 L/kg FPCM. The study emphasized the need for sustainable water management in arid regions, and recommended the adoption of best management practices to enhance WUE.

In Tunisia, Ibidhi and Ben Salem (2020) evaluated the WF and EWP of milk production in eight dairy farms. The study focused on direct (drinking, servicing and cooling water) and indirect (feed production) water consumption. The researchers found that the average WF of 1 kg of FPCM was 1.36 m^3. The green water accounted for 0.93 m^3 and blue water 0.42 m^3. Feed production represented 87% of the total WF, while drinking and servicing water contributed 3.75% and 9%, respectively. The EWP of milk was relatively low, averaging \$0.05/m^3 of water. The authors also analysed scenarios to reduce WF, such as using feed with lower water requirements and improving WUE. This could result in up to 16% reductions in consumptive water use. The authors calculated that efficient use of servicing water could reduce blue WF of milk by up to 4%.

In a study by Al-Bahouh et al. (2021), the blue WF of milk production in Ontario, Canada, was assessed using the WFN methodology. Various water conservation options were estimated by the authors using the AgriSuite software. The study demonstrated that adaptive water conservation practices, such as reusing plate cooler and milk house water, could reduce total water use to 182.7 L/cow/day (a 25.8% reduction) and lower the blue WF to 5.8 L/kg FPCM (a 21.6% reduction). These measures achieved a 77.7% reduction in milk house wash water use from 74.3 L/cow/day to 16.6 L/cow/day.

In the Anand district of India, Saha et al. (2022a) studied effective water use (EWU) while focusing on direct water consumption. They revealed that a single lactating animal consumed an average of 89.02 litres daily, including drinking water, water in feed and cleaning. Unlike traditional approaches that include indirect water consumption such as the water used in producing fodder, this study focused on calculating the moisture content of feed and fodder directly consumed by animals, thereby isolating EWU for milk production. Similarly, the same research group (Saha et al., 2022b) explored the WF of milk production in Banaskantha, Gujarat, focusing on direct water consumption for drinking, feed and cleaning. The study found that a lactating animal consumes an average of 57.34 litres of water per day, including drinking water and water consumed through feed fodder, a lactating animal requires 98.13 litres of water per day in Banaskantha. Daily cleaning water consumption per dairy animal is 12.14 L. The

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

study showed that drinking water has a significant impact on milk production of lactating animals.

In Hungary, Hodúr et al. (2022) investigated, with a focus on milking technologies, the factors contributing to differences in water use and WFs across three large-scale dairy farms. The study revealed that the parallel milking system had the highest blue WF, while the robotic milking system consumed significantly less water. However, the robotic system exhibited the highest grey WF due to increased cleaning requirements. The authors concluded that, from the perspective of minimizing the overall WF, the polygon milking arrangement was the most advantageous compared to both the parallel and robotic milking systems. The findings highlight significant potential for further improvements in milking technology to enhance water efficiency.

Grossi et al. (2022) investigated the impact of cooling management on the WF of milk production in dairy cows. The mean annual WF of the farms was 805 ± 225 litres of water per kg of FPCM, with green water representing the largest share (67.9%) of the total WF. The study found that cooling operations had a minimal impact on the overall milk WF, accounting for only 0.04%.

In Bangladesh, Uddin et al. (2022) applied the methodology developed by the International Farm Comparison Network, which is based on three key pillars: the Typical Farm Approach, the Technology Impact Policy Impact Calculations model and the Dairy Networking Approach (DNA). This methodology was used to evaluate WUE in dairy production systems and to identify the main drivers influencing WUE. The study revealed that approximately 98% of the water required for milk production originated from feed and fodder cultivation, while only 2% was attributed to drinking and service water. Additionally, larger, more productive farms demonstrated higher WUE, achieving values of 0.26 compared to 0.22 observed in smaller farms.

In Hungary, Waltner et al. (2023) studied the interplay between green and blue water use in dairy farming. Feed production accounted for 99.1% of the total WF, with maize silage contributing significantly to green water consumption. Drinking water needs ranged from 74.7 L/cow/day to 101.9 L/cow/day and were influenced by THIs. Servicing water, calculated at 18 L/cow/day, contributed to blue water use. The green water consumption from feed at the studied cattle farm averaged 13 352 lL/cow/day, emphasizing the dominant role of feed production in the overall WF. The authors provided a detailed methodological framework for evaluating both direct and indirect water consumption. The study recommended adaptive strategies, such as adopting thermotolerant breeds and optimizing feeding practices, to mitigate heat stress and improve WUE.

Velarde-Guillén et al. (2023) analysed WF in the arid Peruvian central coast, finding that feed production accounted for 99% of the total WF, with green and blue water contributing 60% and 30%, respectively. The overall WF of

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

dairy production across five dairy farms was calculated to be 0.66 m^3/kg FPCM. The authors stated that imported feed represented a significant portion of the WF, highlighting the need for local, low-water-demand resources to enhance sustainability.

Bronts et al. (2023) analysed the WF of dairy system in the Netherlands and Spain, highlighting the impact of system boundaries and indicator choices on results. The Dutch system demonstrated lower WF values – 0.62 m^3 (green), 0.09 m^3 (blue) and 0.14 m^3 (grey) per kg of milk – due to higher efficiency. In contrast, the Spanish system showed slightly higher figures, with WF values of 0.67 m^3 (green), 0.15 m^3 (blue) and 0.09 m^3 (grey) per kg of milk. Organic systems, characterized by lower efficiency, exhibited larger footprints compared to the Dutch conventional system. Expanding system boundaries to include calves resulted in an 8–15% increase in carbon footprint. The study also noted that green water dominated total WFs, an aspect often excluded in LCA studies. Regarding grey WFs, the authors stated that earlier research included only nitrogen; however, they added that including pesticides in the analysis could yield less favourable outcomes for systems reliant on feed crops rather than grasslands. Additionally, the authors found that water quality standards significantly influenced grey WF calculations.

Expanding the scope of analysis, Rebolledo-Leiva et al. (2024) applied advanced frameworks integrating the water–energy–food (WEF) nexus to assess sustainability in dairy systems. They developed a novel WEF+Circularity Indicator (CEi) that combined water, energy and carbon footprints with food productivity metrics. Applied to 30 dairy farms in Galicia, Spain, the study identified farms with higher circularity percentages as more sustainable. This approach not only incorporated a life cycle perspective but also proposed a framework for guiding a more sustainable and circular food industry. Similarly, Du et al. (2024) studied the eco-efficiency of milk production systems through the water–energy–labour–food nexus in China. The study found that as milk production increased, the resource burdens of large-scale farms were relatively weakened, with the WF dropping by 17% to 8.0 L/kg. The authors' results showed that the resource investment pattern in scale farms shifted from water- and labour-oriented to energy-oriented. Advanced mechanization and on-farm energy production contributed to a 24% improvement in eco-efficiency, underscoring the role of technological innovation in reducing resource burdens.

In Brazil, Palhares et al. (2024) conducted a comprehensive water consumption assessment on 876 dairy farms from January 2021 to December 2022. The study categorized farms into pasture-based, semi-closed and closed systems, analysing water consumption for drinking and cleaning, focusing on two key indicators: litres of water per lactating cow per day (L water/cow/day) and litres of water per kilogram of milk produced (L water kg/milk/day). Closed

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

systems showed the highest water consumption, with an average of 87.5 L/cow/day for drinking and 84.4 L/cow/day for cleaning. In contrast, pasture-based systems showed lower water usage, while semi-confined systems showed the lowest average for drinking water (54.4 L water/cow/day) and pasture systems recorded the lowest cleaning water usage (45.2 L water/cow/day). These findings highlight the need for site-specific water management strategies tailored to farm operations. Methodologically, the researchers implemented continuous monitoring using analogue water meters and adopted some statistical approaches to ensure data reliability.

Similarly, Higham et al. (2024) examined the WF of pastoral dairy farming in New Zealand, analysing 88 farms across three regions. Using the WFN-based blue WF impact index (WFIIblue) and the AWARE water scarcity footprint (WFAWARE), the study identified significant regional disparities. For example, Canterbury’s irrigated farms exhibited up to five times higher blue WF compared to non-irrigated farms in Manawatu and Waikato due to lower rainfall and higher irrigation demands. The study emphasized the importance of using local data and catchment-scale analyses to capture spatial and temporal variations in water availability.

In the Mediterranean region, Ruiz-Colmenero et al. (2024) examined cow milk production in Catalonia, emphasizing the critical role of water availability. Their study revealed that feed production was the largest contributor to the farm stage's WF, particularly when irrigating crops like maize. They proposed strategies such as incorporating low-water-scarcity feed ingredients, improving irrigation systems and enhancing supply chain traceability to mitigate water scarcity impacts.

Firdayati et al. (2024) conducted a holistic analysis of water use in Indonesian dairy farms, incorporating direct and indirect water inputs, including rainwater and grey water reuse. Dairy cattle demonstrated higher WP (0.08 kg milk/L) compared to beef cattle (0.0297 kg beef/L), excluding water required for growing feed. The study’s integrated approach emphasized the importance of combining multiple water sources and reuse strategies to enhance sustainability.

Mohammadi et al. (2024) evaluated livestock WF in Tehran province of Iran, revealing that milk production had the highest WF, averaging 13 007 m^3/ton. Their recommendations included recycled water use and wastewater treatment development to enhance sustainability. In this study, the authors used the methodology introduced by Mekonnen and Hoekstra (2012) for a comprehensive analysis of the WFs associated with various livestock productions is conducted.

In Brazil, Osaki et al. (2024) presented a model based on artificial neural networks to predict water consumption in dairy farms. The model demonstrated good accuracy in predicting water consumption, with an average absolute error

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

of 28.4%. The study suggested that even with limitations on input variables, it was possible to obtain some prediction, although not totally accurate.

Neethirajan (2024) evaluated the transformative potential of big data and AI in advancing the dairy industry towards net zero emissions, with a focus on the Canadian dairy sector. The study highlighted AI-based predictive analytics for optimizing feed efficiency, real-time monitoring through sensor networks and improved energy utilization as key applications that indirectly influence the WF of dairy farming. The author further emphasized that refining processes such as feed management and manure handling can help reduce overall resource use, including water. This research underscored the broader applicability of digital technologies in agriculture, aligning with global efforts towards environmental sustainability and minimizing water usage in dairy production systems.

Fan et al. (2025) explored the environmental impacts of recombining livestock and crop production through recycling animal manure. The study found that full incorporation of manure significantly reduced the WF by 29% compared to semi-incorporation. The improved full incorporation mode, designed based on the water–energy–food nexus, further reduced the WF by 34%, in addition to reductions in energy use and GHG emissions. The authors employed a methodology for calculating the WF in livestock systems based on the WF Assessment Manual (Hoekstra et al., 2011), while excluding the green WF due to its negligible environmental impact.

In Ontario, in Canada Figliuzzi's (2025) study analysed various factors affecting the milking and washing processes, focusing particularly on the volume of water used and its environmental impacts. The study highlighted that the type of milking system, such as tie-in stalls or robotic systems, significantly affects water usage and therefore the farms' water footprint (MCWW). In particular, tie-in stall systems, which are most common in Ontario, tend to use higher water volumes per cow, resulting in higher water consumption per unit of milk production.

These studies collectively emphasize the complexity of assessing and managing the WF in dairy farming. Regional factors, methodological choices and technological advancements play critical roles in determining WF outcomes. By adopting integrated strategies, optimizing feed production and improving WUE, the dairy industry can address sustainability challenges while minimizing environmental impacts.

6 Lessons from case studies

The WF of dairy farming is a crucial metric for evaluating the sustainability of milk production systems. One of the primary concerns in dairy farming WF determination is changes and differences of water use among green, blue and grey water.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

The Water Footprint Standard (Hoekstra et al., 2011) is the method most often chosen by researchers because of its popularity and its ability to distinguish between green, blue and grey water. Due to the current and future impacts of climate change, it is necessary to analyse the water cycle in both the agricultural and housing sectors in order to optimize the process chains in the face of increasing water scarcity. Increasing WP and maximizing WUE in milk production are two strategies for minimizing climate change impacts (Drastig et al., 2010).

In pastoral systems with relatively high rainfall, water scarcity is rarely a concern, but the production of grey water due to pollution remains a significant issue. The presence of excess nitrogen and phosphorus from manure runoff contributes to water contamination, requiring better management practices (Ledgard et al., 2019; Varma et al., 2021). Advanced wastewater treatment technologies can be a potential solution for reducing pollutant loads (Vaishnav et al., 2023)

For intensive dairy units in arid and semi-arid regions, the foremost priority is reducing blue water consumption. As case studies from Kuwait and Tunisia (Al-Bahouh et al., 2020; Ibidhi & Ben Salem, 2020) highlight, drinking and servicing water contribute significantly to the total blue WF in hot climates. Precision irrigation, efficient cooling strategies and feed optimization are essential in these systems to mitigate water stress (Palhares et al. 2019; Ibidhi & Ben Salem, 2020; Grossi et al., 2022; Waltner et al., 2023; Velarde-Guillén et al., 2023). Sensor-based irrigation systems, which adjust water delivery based on real-time soil and crop conditions, have proven effective in minimizing blue water use (Pramanik et al., 2022).

The case studies reviewed emphasize the importance of management interventions in reducing the WF across various dairy production systems. Feed production remains the dominant contributor to overall water consumption. Strategies such as selecting low-water-requirement crops, optimizing feeding efficiencies and utilizing alternative sources can help reduce the indirect WF associated with feed (Palhares et al., 2019; Waltner et al., 2023).

A key takeaway from the studies is the need for integrated assessment methods. Combining WF evaluation with economic and environmental sustainability metrics – such as the WEF or circular economy approaches – can provide a more comprehensive understanding of dairy farm sustainability (Du et al., 2024; Rebolledo-Leiva et al., 2024).

To enhance the clarity and coherence of the analysis, mitigation strategies can be categorized into three key components: feed management, animal management and dairy unit efficiency (Table 1). By implementing these strategies, the dairy industry can improve resource efficiency, minimize environmental impact and contribute to global water sustainability goals.

The water-related processes involved in the life cycle of dairy production are complex and diverse but have not been thoroughly investigated in a

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

Table 1 Categorized mitigation strategies for reducing water footprint in dairy farming

Categories	Grey WR* strategies	Blue WR strategies
Feed management	Nutrient management, optimized manure application, alternative feed sources	Drought-resistant feed crops, precision irrigation
Animal management	Improved feed conversion efficiency, optimized stocking rates	Selective breeding for water efficiency, behavioural adaptation strategies
Dairy unit efficiency	Wastewater treatment, effluent recycling	Water recycling, energy-efficient cooling

*WR: water reduction.

comprehensive, site-specific manner. While research on water use in dairy farming does exist, it often focuses on general estimates rather than detailed, site-specific data that takes into account variations in climate, soil type and farming practices.

The challenge of reducing the WF of dairy production will require a multidisciplinary approach that integrates technological innovation, best management practices and supportive policies. The application of artificial intelligence and big data in dairy management is promising for predictive optimization of water use. Future research should focus on regionalized strategies adapted to specific climatic and environmental conditions, with systems to monitor on-farm consumption in real time, assess the impact of climate change and develop adaptation strategies to ensure that sustainability measures are in line with the availability of local resources.

7 Conclusion

The WF of dairy farming is a critical metric for assessing the sustainability of milk production systems globally. This chapter has outlined key methodologies and frameworks for evaluating the green, blue and grey WFs, highlighting the importance of integrating these metrics with local environmental and climatic conditions. Feed production remains the dominant contributor to the total WF, underscoring the need for sustainable crop and feed management practices.

Technological advancements, such as sensor-based irrigation, PLF and wastewater recycling, present significant opportunities to reduce water use while improving resource efficiency. Case studies from diverse geographies demonstrate the variability in water consumption patterns and the importance of region-specific strategies to enhance WP.

Future efforts should focus on the adoption of innovative water management technologies, the development of comprehensive lifecycle assessments and the integration of artificial intelligence and big data to predict and optimize water usage in dairy systems. By prioritizing these measures, the dairy industry

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

can achieve greater environmental sustainability and contribute to the global agenda of water conservation.

8 Acknowledgements

The authors thank the Portuguese Foundation for Science and Technology (FCT) for the financial support to the Research Centre for Natural Resources, Environment and Society – CERNAS (UIDB/00681).

9 Where to look for further information

A recommended website is the Water Footprint Network (https://www.waterfootprint.org/).

Key literature includes:

- Hoekstra, A., et al. (2011). *The water footprint assessment manual: Setting the global standard*. Earthscan.
- Mekonnen, M. M. & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems*, 15(3), 401–415. https://doi.org/10.1007/S10021-011-9517-8/.
- Hoekstra, A. Y. (2017). Water footprint assessment: evolvement of a new research field. *Water Resources Management*, 31(10), 3061–3081. https://doi.org/10.1007/S11269-017-1618-5.

10 References

Al-Bahouh, M., et al. (2020). Blue and grey water footprints of dairy farms in Kuwait. *Journal of Water Resource and Protection*, 12(7), 618–635. https://doi.org/10.4236/jwarp.2020.127038.

Al-Bahouh, M., et al. (2021). Blue water footprints of Ontario dairy farms. *Water*, 13(18), 2230. https://doi.org/10.3390/w13162230.

Aqeel-Ur-Rehman, A. Z., et al. (2014). A review of wireless sensors and networks' applications in agriculture. *Computer Standards & Interfaces*, 36(2), 263–270. https://doi.org/10.1016/J.CSI.2011.03.004.

Bai, X., et al. (2018). Comprehensive water footprint assessment of the dairy industry chain based on ISO 14046: a case study in China. *Resources, Conservation and Recycling*, 132, 369–375.

Boulay, A. M., et al. (2018). The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *The International Journal of Life Cycle Assessment*, 23, 368–378.

Bronts, S., et al. (2023). The water, land, and carbon footprint of conventional and organic dairy systems in the Netherlands and Spain: a case study into the consequences of ecological indicator selection and methodological choices. *Energy Nexus*, 11, 100217. https://doi.org/10.1016/j.nexus.2023.100217.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

Burton, C. H. & Turner, C. (2003). *Manure Management: Treatment Strategies for Sustainable Agriculture*, Silsoe Research Institute, Bedford, p. 451.

Cai, X. and Rosegrant, M.W. (2003). Chapter 10—World Water Productivity: Current Situation and Future Options. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement,* Kijne, J.W., et al., Eds.; CAB International: Wallingford, UK; pp. 163–178.

Chapagain, A. K. & Hoekstra, A. Y. (2003). Virtual water flows between nations in relation to trade in livestock and livestock products value of water. Research Report Series No. 13. https://www.waterfootprint.org/resources/Report13.pdf.

Chapagain, A. K. & Hoekstra, A. Y. (2004). Water footprints of nations value of water. Research Report Series No. 16. https://www.waterfootprint.org/resources/Report16Vol1.pdf.

Cozzolino, D. (2017). The role of near-infrared sensors to measure water relationships in crops and plants. *Applied Spectroscopy Reviews*, 52(10), 837–849. https://doi.org/10.1080/05704928.2017.1331446.

Cullens, F. (2011, October 8). Water use on dairy farms - MSU Extension. Michigan State University Extension. https://www.canr.msu.edu/news/water_use_on_dairy_farms.

Drastig, K., et al. (2010). Water footprint analysis for the assessment of milk production in Brandenburg (Germany). *Advances in Geosciences*, 27, 65–70. https://doi.org/10.5194/ADGEO-27-65-2010.

Du, X., et al. (2024). Assessing the eco-efficiency of milk production systems using water-energy-labor-food nexus. *Science of the Total Environment*, 955, 176812.

Erina, S., et al. (2013). Research on drinking behavior in the feed consumption time in romanian black and white primiparous cows. *Scientific Papers: Animal Science and Biotechnologies*, 46(1), 387–390.

FAO (2021). Fat–Corrected Milk. Available from: https://web.archive.org/web/20221210141330/. https://www.fao.org/dairy-production-products/resources/glossary/en/?index=f (accessed 29/09/2025).

Fan, X., et al. (2025). Water-energy-food nexus in the sustainable management of crop-livestock coupled systems. *Applied Energy*, 378, 124824. https://doi.org/10.1016/j.apenergy.2023.124824.

Farg, E., et al. (2017). Evaluation of water distribution under pivot irrigation systems using remote sensing imagery in eastern Nile delta. *The Egyptian Journal of Remote Sensing and Space Science*, 20, S13–S19. https://doi.org/10.1016/J.EJRS.2016.12.001.

Figliuzzi, T. (2025). *Characterization of Milking Centre Wash Water for Treatment Feasibility Using On-Site Septic Systems* (Master's thesis, University of Guelph, Guelph, Ontario, Canada). University of Guelph, Guelph.

Firdayati, M., et al. (2024). Study on the use of water and feed resources on beef cattle and dairy farms in Bandung Regency, West Java. *E3S Web of Conferences*, 485, 01007. https://doi.org/10.1051/e3sconf/202448501007.

Flaba, J., et al. (2014). The Design of Dairy Cow and Replacement Heifer Housing Report of the CIGR Section II Working Group. In *Report of the CIGR Section II Working Group N° 14 Cattle Housing*. International Commission of Agricultural and Biosystems Engineering. https://doi.org/10.6092/unibo/amsacta/4272.

Golher, D. M., et al. (2021). Factors influencing water intake in dairy cows: a review. *International Journal of Biometeorology*, 65(4), 617–625. https://doi.org/10.1007/s00484-020-02038-0.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

Grossi, G., et al. (2022). Impact of summer cooling management on milk water footprint in dairy cows. *Journal of Cleaner Production*, 367, 133062. https://doi.org/10.1016/j.jclepro.2022.133062.

Harlia, E., et al. (2024). Management of water sources and liquid waste in dairy farming environments. *BIO Web of Conferences*, 123, 01047. https://doi.org/10.1051/BIOCONF/202412301047.

Higham, C. D., et al. (2017). Water use on nonirrigated pasture-based dairy farms: combining detailed monitoring and modeling to set benchmarks. *Journal of Dairy Science*, 100(1), 828–840. https://doi.org/10.3168/jds.2016-11822.

Higham, C. D., et al. (2024). The water footprint of pastoral dairy farming: the effect of water footprint methods, data sources, and spatial scale. *Water*, 16(3), 391. https://doi.org/10.3390/w16030391.

Hills, J., et al. (2016). Smarter Irrigation for Profit - Increasing Farm Profit Through Efficient Use of Irrigation Input to Dairy Pastures. *7th Australian Dairy Science Symposium (2016)*. Sydney, Australia 16-8.

Hodúr, C., et al. (2022). Blue and gray water footprint of some Hungarian milking parlors. *Water Practice & Technology*, 17(7), 1378. https://doi.org/10.2166/wpt.2022.073.

Hoekstra, A. Y. (2003). Virtual water trade. Proceedings of the International Expert Meeting on Virtual Water Trade, Value of Water Research Report Series No. 12. https://ihedelftrepository.contentdm.oclc.org/digital/collection/p21063coll3/id/10335/.

Hoekstra, A. Y. (2017). Water footprint assessment: evolvement of a new research field. *Water Resources Management*, 31(10), 3061–3081. https://doi.org/10.1007/S11269-017-1618-5/.

Hoekstra, A. Y. & Chapagain, A. K. (2007). Water footprints of nations: water use by people as a function of their consumption pattern. *Water Resources Management*, 21(1), 35–48. https://doi.org/10.1007/S11269-006-9039-X/METRICS.

Hoekstra, A. Y. & Chapagain, A. K. (2008). *Globalization of Water: Sharing the Planet's Freshwater Resources*, Blackwell Publishing, Oxford, pp. 1–208. https://doi.org/10.1002/9780470696224.

Hoekstra, A., et al. (2011). *The Water Footprint Assessment Manual: Setting the Global Standard*. Earthscan, Oxford.

Høgaas Eide, M. (2002). Life cycle assesswment (LCA) of industrial milk production. *International Journal of Life Cycle Assessment*, 7(2), 115–126. https://doi.org/10.1007/BF02978855/METRICS.

IDF. (2010). A Common Carbon Footprint for Dairy. The IDF Guide to Standard Lifecycle Assessment Methodology for the Dairy Industry. *Bulletin of the International Dairy Federation* 445. International Dairy Federation, Brussels, Belgium.

Ibidhi, R. & Ben Salem, H. (2020). Water footprint and economic water productivity assessment of eight dairy cattle farms based on field measurement. *Animal*, 14(1), 180–189. https://doi.org/10.1017/S1751731119001526.

Jawad, H. M., et al. (2017). Energy-efficient wireless sensor networks for precision agriculture: a review. *Sensors*, 17(8), 1781. https://doi.org/10.3390/S17081781.

Jordan, C., et al. (2021). Measuring the effect of improved irrigation technologies on irrigated agricultur: a study case in Central Chile. *Agricultural Water Management*, 257, 107160. https://doi.org/10.1016/J.AGWAT.2021.107160.

Ledgard, S. F., et al. (2019). Nitrogen and carbon footprints of dairy farm systems in China and New Zealand, as influenced by productivity, feed sources and mitigations.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

Agricultural Water Management, 213, 155–163. https://doi.org/10.1016/j.agwat.2018.11.016.

Liao, W.-T. & Su, J.-J. (2019). Evaluation of water scarcity footprint for Taiwanese dairy farming. *Animals*, 9(11), 956. https://doi.org/10.3390/ani9110956.

Lovarelli, D., et al. (2024). Reducing life cycle environmental impacts of milk production through precision livestock farming. *Sustainable Production and Consumption*, 51, 303–314. https://doi.org/10.1016/j.spc.2024.01.013.

Mekonnen, M. & Hoekstra, A. Y. (2010). The green, blue and grey water footprint of animals and animal products, Value of Water Research Report Series No. 48. Unesco-IHE Institute for Water Education. https://research.utwente.nl/en/publications/the-green-blue-and-grey-water-footprint-of-animals-and-animal-pro.

Mekonnen, M. M. & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems*, 15(3), 401–415. https://doi.org/10.1007/S10021-011-9517-8/.

Mendes, W. R., et al. (2019). Fuzzy control system for variable rate irrigation using remote sensing. *Expert Systems with Applications*, 124, 13–24. https://doi.org/10.1016/J.ESWA.2019.01.043.

Meyer, U., et al. (2004). Investigations on the water intake of lactating dairy cows. *Livestock Production Science*, 90(2–3), 117–121. https://doi.org/10.1016/J.LIVPRODSCI.2004.03.005.

Mohammadi, A., et al. (2024). Evaluation of Tehran Province livestock production from water footprint prospective. *Environmental Energy and Economic Research*, 8(2), S082. https://doi.org/10.22097/eeer.2024.437629.1311.

Monteiro, A., et al. (2021). Precision agriculture for crop and livestock farming—brief review. *Animals*, 11(8), 2345. https://doi.org/10.3390/ANI11082345.

Monteiro, A., et al. (2023). Efficient water use in dairy cattle production: a review. *The Open Agriculture Journal*, 17(1), e18743315270668. https://doi.org/10.2174/0118743315270668231127190323.

Murphy, E., et al. (2017). Water footprinting of dairy farming in Ireland. *Journal of Cleaner Production*, 140, 547–555. https://doi.org/10.1016/J.JCLEPRO.2016.07.199.

Nagypál, V., et al. (2020). Sustainable water use considering three Hungarian dairy farms. *Sustainability (Switzerland)*, 12(8), 3145. https://doi.org/10.3390/SU12083145.

Naranjo, A., et al. (2020). Greenhouse gas, water, and land footprint per unit of production of the California dairy industry over 50 years. *Journal of Dairy Science*, 103(4), 3760–3773. https://doi.org/10.3168/JDS.2019-16576/ATTACHMENT/3323AF58-6304-4415-B568-A319FBCE590B/MMC1.PDF.

Neethirajan, S. (2024). Net zero dairy farming—advancing climate goals with big data and artificial intelligence. *Climate*, 12(2), 15. https://doi.org/10.3390/cli12020015.

Ojha, T., et al. (2015). Wireless sensor networks for agriculture: the state-of-the-art in practice and future challenges. *Computers and Electronics in Agriculture*, 118, 66–84. https://doi.org/10.1016/J.COMPAG.2015.08.011.

Osaki, M. R., et al. (2024). Artificial neural network model for water consumption prediction in dairy farms. *Bioscience Journal*, 40, e40256. https://doi.org/10.14393/BJ-V40N0A2024-68845.

Owusu-Sekyere, E., et al. (2017). Economic water productivities along the dairy value chain in South Africa: implications for sustainable and economically efficient water-use Policies in the dairy industry. *Ecological Economics*, 134, 22–28.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

Palhares, J. C. P. & Pezzopane, J. R. M. (2015). Water footprint accounting and scarcity indicators of conventional and organic dairy production systems. *Journal of Cleaner Production*, 93, 299–307. https://doi.org/10.1016/j.jclepro.2015.01.016.

Palhares, J. C. P., et al. (2024). Water performance indicators and benchmarks for dairy production systems. *Water*, 16(2), 330. https://doi.org/10.3390/w16020330.

Palhares, J. C. P., et al. (2019). Best practice production to reduce the water footprint of dairy milk. *Ambiente & Água - An Interdisciplinary Journal of Applied Science*, 14(6), 1–9. https://doi.org/10.4136/ambi-agua.2454.

Palhares, J. C. P., et al. (2020). Best practice production to reduce the water footprint of dairy milk. *Revista Ambiente & Água*, 15(1), e2454. https://doi.org/10.4136/AMBI-AGUA.2.

Pfister, S., et al. (2017). Understanding the LCA and ISO water footprint A response to Hoekstra (2016) "A critique on the water-scarcity weighed water footprint in LCA. Ecological Indicators, 72, 352-259. http dx.doi.og 10.1016 j.ecolind.2016.07.051.

Pramanik, M., et al. (2022). Automation of soil moisture sensor-based basin irrigation system. *Smart Agricultural Technology*, 2, 100032. https://doi.org/10.1016/j.ter.2022.100032.

Perry, C., et al. (2023). Water Consumption, Measurements and Sustainable Water User (Technical Report). https://watercommission.org/publication/water-consumption-measurements-and-sustainable-water-use/.

Rebolledo-Leiva, R., et al. (2024). Embedding water-energy-food nexus and circularity assessment for organization benchmarking: a case study for dairy farms. *Waste Management*, 189, 410–420.

Ridoutt, B. G., et al. (2010). Short communication: the water footprint of dairy products: case study involving skim milk powder. *Journal of Dairy Science*, 93(11), 5114–5117. https://doi.org/10.3168/JDS.2010-3546.

Robinson, A. D., et al. (2016). Usage and attitudes of water conservation on Ontario dairy farms. *Professional Animal Scientist*, 32(2), 236–242. https://doi.org/10.15232/pas.2015-01468.

Romaguera, M., et al. (2010). Potential of using remote sensing techniques for global assessment of water footprint of crops. *Remote Sensing*, 2(4), 1177–1196. https://doi.org/10.3390/RS2041177.

Ruane, E. M., et al. (2011). On-farm treatment of dairy soiled water using aerobic woodchip filters. *Water Research*, 45(20), 6668–6676. https://doi.org/10.1016/J.WATRES.2011.09.055.

Ruiz-Colmenero, M., et al. (2024). Challenges when assessing water-related environmental impacts of livestock farming: a case study of a cow milk production system in Catalonia. *Water*, 16, 1299. https://doi.org/10.3390/w16091299.

Saha, U. S., et al. (2022a). Water footprint of milk production in India: a case of Anand district of Gujarat (Working Paper No. 336). Institute of Rural Management Anand. https://www.irma.ac.in.

Saha, U. S., et al. (2022b). Water footprint of milk production in the Banaskantha district of Gujarat (Working Paper 337). Institute of Rural Management Anand. https://www.irma.ac.in.

Salcedo, G., et al. (2022). Water footprint of dairy farms according to typology of feeding. *ITEA Informacion Tecnica Economica Agraria*, 118(4), 547–564. https://doi.org/10.12706/itea.2021.040.

Shine, P., et al. (2018). Multiple linear regression modelling of on-farm direct water and electricity consumption on pasture based dairy farms. *Computers and Electronics in Agriculture*, 148, 337–346. https://doi.org/10.1016/j.compag.2018.02.020.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.

Shine, P., et al. (2020a). A global review of monitoring, modeling, and analyses of water demand in dairy farming. *Sustainability (Switzerland)*, 12(17), 7012. https://doi.org/10.3390/SU12177201.

Shine, P., et al. (2020b). Energy consumption on dairy farms: a review of monitoring, prediction modelling, and analyses. *Energies*, 13(5), 1288. https://doi.org/10.3390/EN13051288.

Sommer, S. G., et al. (2013). *Animal Manure Recycling: Treatment and Management*, Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 1–364. https://doi.org/10.1002/9781118676677.

Sultana, M. N., et al. (2014). Comparison of water use in global milk production for different typical farms. *Agricultural Systems*, 129, 9–21. https://doi.org/10.1016/j.agsy.2014.05.002.

Uddin, M. M., et al. (2022). Estimation of water requirement and water use efficiency in typical dairy farms in Bangladesh. *Journal of Innovative Agriculture and Social Development*, 1(1), 23–32.

USDA. (2012). Part 651-Agricultural Waste Management Field Handbook. In *Handbook Natural Resources Conservation Service*. United States Department of Agriculture (USDA). https://directives.nrcs.usda.gov/sites/default/files2/1712930985/Part%20651%20-%20Agricultural%20Waste%20Management%20Field%20Handbook.pdf.

Vaishnav, S., et al. (2023). Livestock and poultry farm wastewater treatment and its valorization for generating value-added products: recent updates and way forward. *Bioresource Technology*, 382, 129170. https://doi.org/10.1016/j.biortech.2023.129170.

Vallejo-Gómez, D., et al. (2023). Smart irrigation systems in agriculture: a systematic review. *Agronomy*, 13(2), 342. https://doi.org/10.3390/AGRONOMY13020342.

Varma, V. S., et al. (2021). Dairy and swine manure management – challenges and perspectives for sustainable treatment technology. *Science of the Total Environment*, 778, 146319. https://doi.org/10.1016/j.scitotenv.2021.146319.

Velarde-Guillén, J., et al. (2023). Water footprint of small-scale dairy farms in the central coast of Peru. *Tropical Animal Health and Production*, 55(1), 25. https://doi.org/10.1007/s11250-022-03437-8.

Vourch, M., et al. (2008). Treatment of dairy industry wastewater by reverse osmosis for water reuse. *Desalination*, 219(1–3), 190–202. https://doi.org/10.1016/J.DESAL.2007.05.013.

Waltner, I., et al. (2023). Influence of climatic factors on the water footprint of dairy cattle production in Hungary—a case study. *Water*, 15(18), 4181. https://doi.org/10.3390/w15234181.

Willers, H. C., et al. (1999). Potential of closed water systems on dairy farms. *Water Science and Technology*, 39(5), 113–119. https://doi.org/10.1016/S0273-1223(99)00092-X.

Zhang, G. P., et al. (2013). Water footprint assessment (WFA) for better water governance and sustainable development. *Water Resources and Industry*, 1–2, 1–6. https://doi.org/10.1016/J.WRI.2013.06.004.

© Burleigh Dodds Science Publishing Limited, 2026. All rights reserved.