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Article

Impacts of Livestock Species and Farm Size on Blue Water Productivity and Water Scarcity Footprint of Dairy Farming Sheds in Punjab State (India)

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Abstract

A robust analysis of water use in major food production systems is crucial for improving their productivity and sustainability in water-scarce arid and semi-arid regions like Punjab (India) facing the depletion of groundwater resources. This study aimed to assess blue water use and blue water productivity in dairy farming systems across different farm sizes in Punjab. Comprehensive monitoring and assessment of water use over a full year (from July 2022 to June 2023) was conducted on 24 dairy farm sheds in Punjab, revealing significant variability in their blue water use (measured in *L per adult animal per day*) and blue water productivity quantified as *kg of fat- and protein-corrected milk (FPCM) produced* per m^3 of the blue water consumed. The variability was influenced by factors such as livestock species, farm size (medium with 15–25 livestock, large with 25–100 livestock, and commercial with >100 livestock), bathing and servicing routines, and energy use patterns. The average dairy livestock total blue water consumption varied from 112 ± 14 to 131 ± 19 L per adult animal per day, with 20–40% higher livestock drinking water and about six times higher livestock bathing and serving water used during the summer months. Interestingly, a large share (45%) of the average total blue water consumption is contributed by indirect water consumption via the use of energy (electricity and diesel) in dairy farm sheds. Dairy milk blue water productivity was quantified higher, ranging from 154 ± 11 to 225 ± 59 kg *FPCM* per m^3 in buffalo- and crossbred cattle-based dairy farm sheds. However, indigenous cattle showed a lower blue water productivity ranging from 56 to 97 kg *FPCM* per m^3, reflecting their lower milk yields and limited use of intensified management practices. The state-level water scarcity footprint (*WSF*) of Punjab dairy farm sheds was quantified at 4870 million m^3 world-eq, which showed a significant spatial variation among Punjab districts. However, the results of this study offer novel seasonally and spatially disaggregated benchmarks of blue water consumption, blue water productivity, and the water scarcity footprint of Punjab's dairy farming sheds. This new information is crucial for the development of locally calibrated and validated models for improving the water productivity and sustainability of dairy farming across Punjab and other similar arid and semi-arid regions in Southeast Asian countries.

Keywords: dairy farming; buffalo; crossbred; livestock water; milk production; water use; energy usage; water footprint; water impact

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1. Introduction

Water is a vital resource in agriculture, and its productivity and sustainability are strongly shaped by the robust continued assessment and management of water use in major agricultural food production systems worldwide. As defined in ISO 14046:2014 (Clause 3.2.1), “water use” refers to the use of water by human activity, including withdrawals, discharges, and in-stream impacts such as those associated with livestock production. In contrast, “water consumption” describes the portion of water use that is not returned to the same basin, typically due to evaporation or transpiration, and therefore represents a net loss (consumption) rather than the use of water. Blue water refers to surface and groundwater resources used and consumed in different production and servicing activities.

Provision of a sustainable water supply is a cornerstone of dairy farming operations, playing a crucial role in the direct use and consumption of blue water by dairy livestock drinking, livestock bathing, and the cleaning and cooling systems of dairy farm sheds. Dairy farming also consumes blue water indirectly in terms of energy (e.g., electricity) and other inputs used in dairy production systems. Livestock production currently uses roughly two-fifths of all agricultural consumptive water, mainly through water embodied in feed, highlighting its central role in the global water–food challenge [1]. A comprehensive analysis of livestock farming water use is key to identifying hot spots and options to improve livestock water productivity and reduce its environmental impacts. To address these challenges, global initiatives such as the FAO’s Livestock Environmental Assessment and Performance (LEAP) partnership has published standardized guidelines entitled “Water use in livestock production systems and supply chains—Guidelines for assessment” for assessing water productivity and water scarcity footprints in livestock production systems and supply chains [2]. However, despite the standardized frameworks and guidelines available, a lack of localized measurements and locally tailored livestock water use databases and models continue to hinder progress in a robust assessment of water use, its productivity, and environmental impact in livestock production systems and supply chains, particularly in increasingly water-scarce and rapidly developing regions like Northwestern India. Within this global context of increasing pressure on water resources, countries with large and rapidly expanding dairy sectors, such as India, face particularly significant challenges in ensuring sustainable water use in dairy milk production.

India stands as the largest global producer of dairy milk, contributing 24% of the total global dairy milk production [3]. The nation’s dairy sector is integral to its food security, rural livelihoods, and economic development in India’s rural landscapes. Punjab, one of India’s leading dairy milk-producing states, contributes 6.4% to the national milk pool despite having only 2.2% of the country’s dairy bovine population [4]. However, known historically for its agricultural transformation during the Green Revolution, today Punjab faces severe groundwater depletion due to its limited rainfall (mainly semi-arid region) and cultivation of water-intensive crops like wheat and rice and other intensive agricultural and industrial activities [5]. A shift towards livestock dairy farming as a high-income alternative to traditional cropping systems is being promoted to diversify land use and rural livelihoods across Punjab [6]. Within India, Punjab represents a critical case where high dairy production coincides with severe groundwater depletion and increasing stress on water resources.

However, livestock dairy farming in semi-arid regions like Punjab is not without its challenges. Water use on dairy farms varies widely depending on factors such as livestock type, feed quality, farm size, and local management practices and climatic conditions. A robust quantification of water use, including direct (e.g., livestock drinking, bathing, and servicing waters) and indirect (e.g., water for feed cultivation and energy requirements), is essential to understanding and improving the productivity and sustainability of water use in dairy livestock production systems in Punjab and other similar regions. Farooq and Shahid [7], along with Al-Bahouh et al. [8], emphasized the importance of quantifying on-farm water use and comprehending water use patterns in different production setups, including dairy farming. Despite the growing importance of dairy farming in such water-stressed regions like Punjab, a comprehensive understanding of water use at the farm level remains limited. Most existing studies on the assessment of water use in dairy production in India have primarily focused on aggregate water use metrics, often neglecting spatial and seasonal variations in direct and/or indirect water use patterns. For instance, studies in Gujarat [8], Kerala [9], and Punjab [10,11] have analyzed dairy water productivity, but they are somewhat limited to account for the potential impacts of seasonal climatic variations and different livestock species on the water use of different dairy livestock farms. Sharma et al. [12] quantified the direct and indirect blue water use and blue water productivity of dairy milk processing plants in Punjab but not the blue water use and its productivity in dairy farming sheds. Furthermore, few studies have examined the combined effects of different livestock species, dairy farm shed sizes, and dairy farm shed operations on direct and indirect water use and its productivity in dairy farming operations in the arid and semi-arid regions of India and other Southeast Asian countries.

This study was carried out for a comprehensive assessment of blue water use and its productivity in dairy farming sheds across the Punjab state in India. It included the assessment of blue water (groundwater), excluding the use of green water stemming from precipitation. The use of green water is considered less relevant for the assessment of blue water scarcity impacts of agriculture production systems. Following Ridoutt et al. [13], the potential environmental impacts associated with the consumption of so-called green water, derived from natural rainfall over agricultural lands, is not equivalent to so-called blue water withdrawn from surface and groundwater resources. However, this study did focus on the direct and indirect use and consumption of blue water in dairy farm shed operations, excluding dairy livestock feed production. The study aimed to quantify the potential impacts of dairy farm shed size, livestock species, and seasonal climatic conditions on blue water use and consumption in livestock drinking, bathing, and the cleaning and cooling operations of dairy farm sheds. The specific objectives of the study were to (1) measure and quantify both direct and indirect blue water use in representative dairy farm sheds across the study area, (2) analyze potential impacts of livestock species, dairy farm shed size, and seasons on direct blue water use, blue water consumption, blue water productivity, and water scarcity footprint per unit of dairy milk production, and (3) assess potential environmental water scarcity impacts of dairy farming sheds' blue water use in different climactic zones of the study area.

The study of dairy farming systems in Punjab, with its representative arid and semi-arid climatic zones with varying rainfall patterns in Northwest India, provides an ideal case study for addressing current research gaps by offering novel insights for the development of locally relevant livestock water use datasets and models available for the robust quantification of water productivity and water scarcity footprints of livestock dairy production systems in India and other Southwest Asian countries. Despite the increasing focus on water resource management in agriculture, there is a lack of region-specific and empirical studies quantifying blue water use, water productivity, and water scarcity footprints in the dairy farming systems of Punjab and other semi-arid regions in Northwest India. Existing studies are often limited in scope and do not adequately account for variations in livestock species, farm size, and seasonal climatic conditions. Furthermore, the absence of locally validated datasets and integrated assessment approaches restricts the accurate evaluation of environmental water impacts in these systems. Therefore, this study addresses these limitations by providing a comprehensive and location-specific assessment of blue water use and its environmental impacts across different dairy farming systems in Punjab. Additionally, this study not only aims to contribute to the academic discourse on productive and sustainable water resource management but also offers practical insights for policymakers and stakeholders seeking to optimize water productivity in dairy production systems in the arid and semi-arid regions of India and other similar climatic conditions in Southwest Asian countries.

2. Methods and Material

2.1. The Study Area

The study area of Punjab state is located in the northwestern part of India and covers an area of 50,362 km^2, which is 1.53% of the total geographical area of the country. Punjab is mostly spread over a flat alluvial plain except for a thin belt along the northeastern border where it is mountainous. In the southwestern parts of Punjab state, there are stable sand dunes dotting the landscape. The climate of Punjab state is semi-humid to semi-arid in the north, arid in the south and southwest, and semi-arid in the remaining part of the state. It has a well-defined rainy season from July to September, when almost 80% of the annual rainfall takes place due to the southwestern monsoon. The remaining 20% of the annual rainfall takes place during winter months from December to March. The annual rainfall in Punjab state varies from about 1000 mm in the northeast to less than 300 mm in the southwest. The sub-mountainous region, i.e., a High Rainfall Zone, receives more than 800 mm of rainfall annually, while the central zone, i.e., a medium rainfall zone, receives around 400–650 mm of rainfall annually (Figure 1). The Southwestern Zone, i.e., a low rainfall zone, receives the lowest rainfall, being less than 400 mm of the annual rainfall (Figure 1). Groundwater is a dominant source of water supplies for agriculture, drinking, and other activities in rural areas. However, about 78% of the state is affected by groundwater stress, and the majority (more than 80% of the groundwater-stressed blocks) lies in the medium and low rainfall zones of Punjab [14].

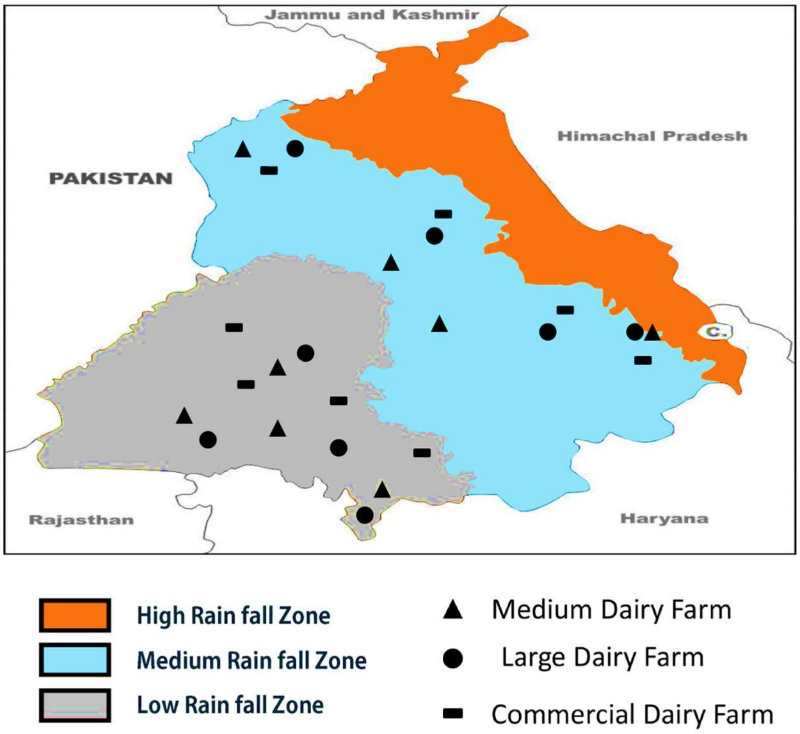

Figure 1. Map of different climatic (rainfall) zones and locations of the selected dairy farming sheds for study in Punjab state (India).

2.2. The Study Variables

A total of 24 dairy farm sheds were surveyed and selected in low to medium rainfall zones in the study area (Figure 1). The size of dairy farm sheds in Punjab varies from less than 5 to more than 100 dairy animals [15]. The prevailing dairy production systems in Punjab state fall into one of four categories, described as follows. (I) Landless/Domestic Dairy Farmers: these farmers have a low number of bovine (average size is 1 to 2), and these livestock are mostly sold by large farmers to small/medium farmers, and ultimately, they remain with landless farmers. (II) Small and Medium Rural Dairy Farmers: They are generally of mixed dairy livestock types (both buffalo and cattle) on the farm. They mainly have less than 25 dairy livestock producing low to medium milk yield (<20 kg/liters of milk per livestock per day). (III) Large Dairy Farms: They have 25–100 livestock and are mainly owned by large landholders. They are generally of mixed dairy livestock types, with about 60% crossbred and 30% buffaloes, and the remaining 10% are indigenous cattle like *Sahiwal*. (IV) Commercial Dairy Farms: They are typically one dairy livestock species enterprises, majorly comprising crossbred cattle. These farms vary in size from 100 to 500 high-yielding dairy livestock (>20 kg/liters of milk per livestock per day) cattle breeds.

A list of dairy farming sheds operating in the low and medium rainfall districts of Punjab (Figure 1) was prepared using information from local veterinary hospitals. The dairy farm sheds were then categorized based on their livestock size as medium (15 to 25 livestock), large (25 to 100 livestock), and commercial (>100 livestock) dairy farm sheds. A stratified sampling approach was adopted to ensure representation across different dairy farm sizes and agro-climatic (i.e., low and medium rainfall) conditions. Within each category, four (4) dairy farm sheds were selected randomly from the prepared list. A total of 24 dairy farm sheds were selected as representatives of the three different farm sizes, i.e., eight (8) farms per each farm size category of the medium (15 to 25 livestock), large (25 to 100 livestock), and commercial (>100 livestock) dairy farm sheds. Spatially, four (4) dairy farm sheds for each dairy farm size, commercial, large, and medium, were selected in the medium rainfall zone (Figures 1 and 2). Similarly, four (4) dairy farm sheds from each dairy farm size, commercial, large, and medium, were selected throughout the low rainfall zone (Figures 1 and 2). The selected dairy farms were doing mixed farming, rearing both cattle and buffaloes for dairy milk production. A majority of the selected dairy farm sheds had crossbred cattle. However, seven (7) dairy farm sheds were also rearing indigenous dairy cattle like *Sahiwal*. Table 1 summarizes the herd size and the average milk yield of cattle and buffaloes at the selected dairy farm sheds. Dairy livestock of different age categories, like calves (0–3, 3–6, and 6–12 months), heifers (1–2 years and 2–3 years), and lactating and pregnant crossbred cattle, indigenous cattle, and buffaloes were enrolled in the study. However, cattle like *Hariyana*, *Sahiwal*, etc., of 300 to 500 kg of body weight cannot be compared with *Murrah* and *Nili ravi* buffaloes of 700 to 800 kg body weight. For an equitable understanding of bovine, Sirohi et al. [16] have standardized Adult Livestock Units using factors, viz. bodyweight, and labor utilization patterns of animals. The number of livestock at the selected dairy farm sheds were converted into Adult Livestock size by the Adult Livestock Unit Converter [16]. These animals in the selected farms were fed a combination of green fodder (e.g., maize, sorghum, and barseem), dry fodder (wheat straw), and concentrate feed.

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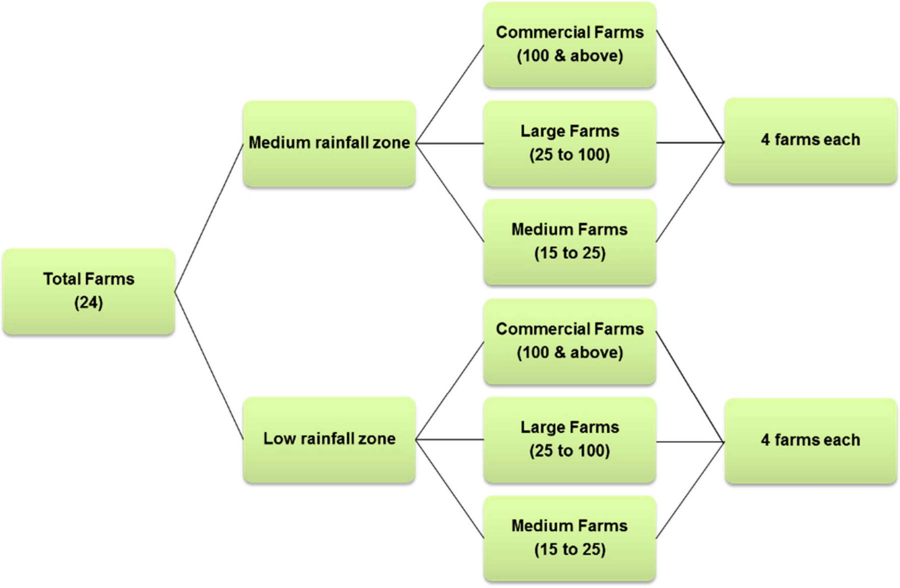

Figure 2. Outline of the dairy farm sheds selected across the study area, Punjab state (India).

Table 1. Summary of the dairy farm sheds studied for quantification of blue water use, blue water productivity, and water scarcity footprints of dairy milk production in Punjab state (India) during the year 2022–2023.

Farm Size Type	Medium (450–600 mm) Rainfall Zone			Low (<400 mm) Rainfall Zone		
	Average Herd Size	Adult Unit Convertor	Average Milk Yield (kg/animal/day)	Average Herd Size	Adult Unit Convertor	Average Milk Yield (kg/animal/day)
Medium Farms	24 (22–25)	23	7.50 (9.76)	21 (19–25)	29	6.81 (8.94)
Large Farms	63 (31–90)	70	7.89 (9.48)	62 (53–74)	67	7.38 (9.65)
Commercial Farms	133 (104–238)	137	9.29 (11.72)	101 (100–124)	102	6.79 (9.89)

Note: Figures in parentheses indicate the milk yield in *FPCM* (kg/animal/day).

2.3. Monitoring of Dairy Farm Sheds

The selected dairy farm sheds were monitored for their blue water use and milk production over one year, from July 2022 to June 2023. A comprehensive questionnaire was developed to collate the required data for direct and indirect water used in different operations and management activities at the studied dairy farm sheds (Figure 3). Groundwater was identified as the source of water supply at the selected dairy farms. Water was mainly used for dairy livestock drinking, bathing, and shed cleaning services at each dairy farm shed [17]. However, the indirect water consumption in the form of energy used at the studied dairy farm sheds was quantified and included in the assessment here. The data collected for different water use activities and energy uses were systematically recorded monthly through the well-defined questionnaire, as follows:

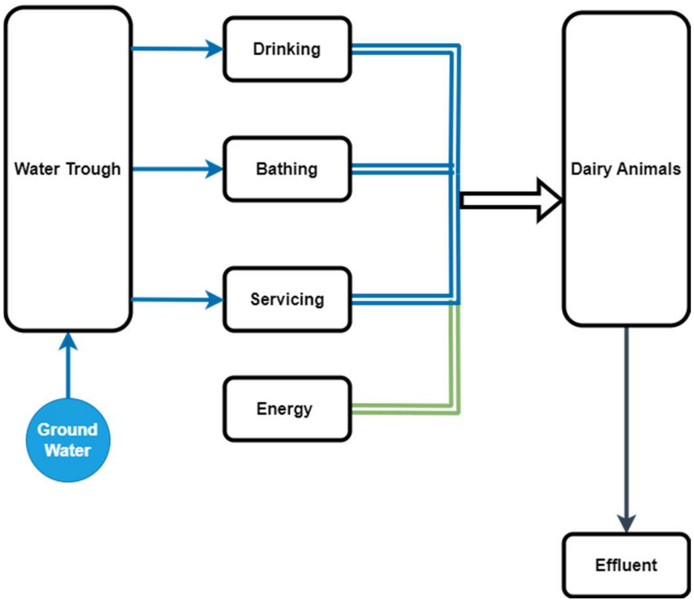

Figure 3. Schematic of direct and indirect blue water use activities included for water use data collection on the studied dairy farms.

(a) Livestock drinking water

The livestock drinking water was provided via water troughs, which served all kinds of livestock on the farm sheds. The consumption of monthly livestock drinking water was quantified by the number of water troughs used, size of the water trough, and by records of how often they were filled each day (Table 1). The dairy shed farmer recorded daily fillings of livestock drinking water troughs on their farms. This measurement assumed that the water troughs were empty when they were refilled by the farmer. With the number of livestock drinking water troughs ranging from 3 to 8, commercial dairy farms had the highest average water trough storage capacity (2612 ± 1066 L), followed by large-size farms (1705 ± 607 L), with a number of 1 to 7 water troughs, and medium-size farms (602 ± 212 L), with a number of 1 to 2 water troughs only. Approximately 10–12 animals drink from each water trough on the selected dairy farms.

(b) Servicing of dairy farm sheds

Servicing water at the selected dairy farm sheds was used for cleaning the dairy sheds and washing milking utensils. The servicing water was quantified by recording the size resp. flow rate of water cleaning pipes and their daily usage duration for servicing the farm sheds (Table 2). The selected dairy farms had open paddocks and covered sheds. The open paddocks are generally cleaned in the evening, and the covered sheds, also known as the standing spaces, are generally cleaned in the morning for all kinds of animals at the studied dairy farm sheds. The covered sheds generally have hard surface floors and are generally cleaned by water after scraping the dung, feed, and fodder waste. The size and flow rate of the water pipe used for cleaning services were established by direct measurements using a volumetric method by measuring the time required to fill a container of known volume and the duration of their daily water use, which was recorded by the farmers at each of the studied dairy farms. The established flow rate and daily recordings of the duration of water pumping were multiplied to quantify the amount of water used for cleaning services at each farm per day (Table 2).

Table 2. Outline of dairy farm data collection and analysis framework for quantification of blue water use and consumption for dairy milk production at the studied dairy farms in Punjab state (India) during the year 2022–2023.

Water Indicator	Variable	Collection of Data	Per Animal Assessment	Per kg *FPCM* Assessment
Direct Blue Water Usage	Bathing and Washing	Mode of bathing (buckets/pipe). If buckets, records of capacity of bucket and no. of buckets used. If pipe, records of size (flow rate) of water pipe and total duration of water pumping.	Total direct water used (L)/ number of Adult Animal Units	Total direct water used (L)/ kg of *FPCM* produced
	Servicing	Records of the size (flow rate) of water pipes used & duration of water pumping.		
Direct Blue Water Consumption	Drinking	Number and size of water troughs and their storage capacity (L). Records of water trough filling frequency in a day.	Total drinking water consumed (L)/number of Adult Animal Units	Total drinking water consumed (L)/kg of *FPCM* produced
Indirect Blue Water Consumption	Electricity	Total electricity units consumed converted to water consumed using water consumed per unit in electricity generation.	Total indirect water consumed (L) in the form of electricity generation and diesel used/number of Adult Animal Units	Total indirect water consumed (L) in the form of electricity generation and diesel used/kg of *FPCM* produced
	Diesel	Total liters of diesel consumed converted into water consumed using existing literature for water consumed per L of diesel production in refinery.		

(c) Bathing and washing of animals

Water buckets or water pipes are typically used to bathe and wash dairy livestock on the studied farms. Therefore, animal bathing and washing water was quantified by daily measurements of animal bathing and washing taken at the selected farms in summer and winter seasons. The capacity, number, and size of the water buckets/pipes, as well as the duration of the water pumping operation, were recorded and used to quantify the amount of animal bathing and washing water used on each farm. The capacity of each water bucket and the total number of buckets used per livestock were first determined if the farmers used the water buckets for bathing and washing their livestock on their farms. The sum of the water in each bucket was used to quantify the total amount of water used for animal baths and washing. If a water pipe was being used, the water pumping duration was measured and combined with the pipe's size/flow rate to quantify the total amount of water used for livestock baths and washing (Table 2). The frequency of animal bathing and washing across seasons was recorded daily by dairy farmers and verified during field visits. The total water used was quantified by combining the number of bathing events with the volume of water used per event, calculated either from bucket capacity or pipe flow rate and duration.

(d) Energy Usage

The monthly electricity bill and diesel consumption were recorded from the studied dairy farm sheds. In the farm surveys, each farmer provided their monthly electricity bill and monthly expenditure on diesel consumption from July 2022 to June 2023. The records of electricity and diesel consumption were converted into indirect blue water consumption using the calculations described in Section 2.4 below.

(e) Milk Yield

The milk yield of each studied dairy farm was recorded daily by dairy farmers, which was then converted into *Fat- and Protein-Corrected Milk* (*FPCM*) according to the International Dairy Federation [18]'s conversion formula as follows:

$$FPCM\left(\frac{\frac{kg}{animal}}{day}\right) = milk\ Yield\ (kg/animal/day) * (0.1226 * fat\% + 0.0776 * protein\% + 0.2534)$$

The mean values of protein and fat content were defined based on the milk data surveyed by the study farmers and applied with a correction factor of fat and protein value collected from MILKFED (The Punjab State Cooperative Milk Producers' Federation Limited, Chandigarh, Punjab, India). The fat content for cattle and buffalo milks was considered at 3.92% and 7.38%, respectively, during the summer season (April to October) and at 4.04% and 7.12%, respectively, during the winter season (November to March). The protein for cattle and buffalo milk was considered to be 3.05% and 4.09%, respectively, during the summer season and at 3.16% and 3.91% respectively, during the winter season.

The collection of water and energy use and milk production data at the studied dairy farm sheds were cross-verified through monthly field visit observations and repeated interactions with farmers to ensure accuracy and consistency.

2.4. Quantification of Water Use and Consumption at Dairy Farm Sheds

The collected blue water use and related milk production data at the studied dairy farm sheds were analyzed to quantify direct and indirect blue water use and blue water consumption and dairy milk blue water productivity and water scarcity footprint, as per the methods, standard terminologies, and empirical procedures explained by Hoekstra et al. [19] and FAO LEAP Water guidelines [2], excluding green water aspects. Conceptually, the groundwater utilized on the studied dairy farms was quantified as the blue water used for dairy farming in the study area. Using the water use data collected (as outlined in Table 2), the following three water use indicators were calculated to analyze different forms of blue water used and consumed at the dairy farm shed, as follows:

(a) Direct blue water use

Quantification of direct blue water use accounted for the total direct water used for livestock drinking water supplies, bathing and washing dairy animals, and cleaning services of the dairy farm sheds, expressed as follows:

Direct blue water use (L of water per kg of FPCM) = Direct blue water use (i.e., direct water use in livestock drinking supply, bathing, and washing and servicing of dairy farm shed) (L)/kg of FPCM (1)

(b) Direct blue water consumption

Direct blue water use for bathing and washing dairy animals and farm sheds' cleaning services is not considered to be all of the consumed blue water, as it is generally returned as effluent discharges on the dairy farms [19,20]. However, the livestock drinking water is considered to be consumed water [19,21]. Therefore, direct blue water consumption accounted for only the direct blue water consumed (i.e., the water used in the livestock drinking activities) on the studied dairy farms, expressed as follows:

Direct blue water consumption (L of water per kg of FPCM) = Direct blue water consumed (i.e., direct water consumed in livestock drinking supply) (L)/kg of FPCM (2)

(c) Indirect blue water consumption

Quantification of indirect blue water consumption was associated with the energy and fuel consumption used in the operation and maintenance of the studied dairy farms. Firstly, records of monthly electricity and diesel consumption were converted to indirect water consumption equivalents using the conversion factors of blue water consumed (L) per unit of electricity generation produced and diesel fuel refined, respectively. The indirect blue water consumed per livestock was then quantified based on the total indirect blue water consumption related to the electricity and diesel consumption and the number of Adult Animal Units on the studied farms (Table 2).

About 74% of Punjab's electricity comes from thermal energy, with the remaining portion coming from hydropower [22]. In 2012, the Central Electricity Authority (CEA, India) [23] estimated that for every gigajoule of electricity generated from coal, approximately 18,000 L of water is consumed; and in the case of hydro energy, the water consumption was estimated at 9222 L/GJ for the Bhakhra Dam, Ranjit Sagar Dam, Pong Dam, UBDC, Mukerian, and Anandpur Sahib Hydel Projects, which are located in lower Punjab and Himachal Pradesh, the major sources of hydro energy supplied in the study area [12]. These estimates of the water consumption of thermal electricity (18.00 m^3/GJ) [23] and hydropower (9.22 m^3/GJ) [12] were then averaged using the ratios of 0.74 and 0.26, respectively, to quantify the average indirect water consumption of electricity supply for the studied farms. However, it is noteworthy to mention that, at all of the studied dairy farms, diesel consumption also served as the primary energy source. The indirect blue water consumption of diesel fuel was quantified, using the existing literature, as per 0.40 L of blue water consumed for every 1 L of diesel produced in diesel refineries [24]. Using the estimates of the above-described water consumption of electricity and diesel supplies, the indirect water consumption associated with the energy consumption on the studied dairy farms was quantified as follows:

$$\begin{gathered}\textit{Indirect blue water consumption (L of water per kg FPCM) = [Disel fuel consumed} \\ \textit{(L)* average water consumed in diesel production (L of water per liter of diesel) +} \\ \textit{Electricity consumed (GJ)* average water consumed of Punjab electricity} \\ \textit{(L/GJ)]/kg of FPCM}\end{gathered} \tag{3}$$

Finally, the total blue water consumption (L of water per kg *FPCM*) was quantified as the sum of the direct blue water consumption (Equation (2)) and indirect blue water consumption (Equation (3)) for the studied dairy farms.

2.5. Quantification of Blue Water Productivity and Water Scarcity Footprint at Dairy Farm Sheds

The dairy milk blue water productivity was calculated as per the FAO LEAP Water Use Guidelines [2], excluding the green water aspects. Here, the total blue water consumed indirectly in energy usage and directly on-farm activities such as livestock drinking at the studied dairy farm sheds was taken into account, as follows:

$$\textit{Blue Water Productivity}\ (\mathrm{kg}\ \textit{FPCM}/\mathrm{m}^3) = \frac{\textit{Milk yield}\ (\mathrm{kg}\ \textit{FPCM})}{\textit{Total Blue Water Consumption}\ (\mathrm{m}^3)} \tag{4}$$

This approach enabled the consistent quantification and assessment of different livestock species and farm sizes on blue water productivity of dairy milk production at the studied dairy farm sheds. The contribution of dairy farming to water scarcity was assessed by quantification of dairy farming water scarcity footprint (*WSF*) for each district and the whole of the Punjab state. The dairy water scarcity footprint (*WSF*) was quantified, following the ISO 14046 [20], as suggested in the FAO LEAP Water Use Guidelines [2], using the AWARE characterization factor for non-agricultural water use, as follows:

$$\text{Water Scarcity Footprint }(WSF)\left(\mathrm{m^3\ world-eq}\right) = V\left(\mathrm{m^3}\right) \times CF\left(\mathrm{m^3worldeqperm^3}\right) \quad (5)$$

where V represents the volume of blue water consumed directly by dairy farming operations, expressed in cubic meters ($\mathrm{m^3}$), in the study districts, and CF is the AWARE characterization factor for water scarcity impacts [25]. The CF selection reflects that all reported dairy water use was non-irrigation water. Use of the AWARE is recommended for site-specific water scarcity assessment due to its spatial differentiation and high resolution. The CF value for the whole of Punjab (50.3 $\mathrm{m^3}$ world-eq per $\mathrm{m^3}$) was extracted and used from the global layer produced by WULCA [26]. However, the available state level CF for Punjab was also applied for quantification of the district-wise WSF of dairy farming across different districts of the Punjab state, as the district-wise CF level was not available.

The quantified district-level WSF values were imported into Python version 3.9 (Matplotlib library) to generate a heatmap illustrating spatial disparities in scarcity impacts. Two color schemes, i.e., Plasma for district-wise WSF and Viridis for the aggregated Punjab value, were used to enhance visibility. In the district panel, color intensity increases with WSF magnitude, where darker shades indicate relatively lower WSF values and brighter shades represent relatively higher WSF scarcity impacts, enabling clear identification of high WSF impact districts. The aggregated Punjab WSF was displayed separately to avoid distortion due to its much larger magnitude compared to the individual districts. A two-panel visualization was thus produced, combining the district heatmap and the Punjab-level heatmap to facilitate simultaneous interpretation of spatial variability and the cumulative state-level water scarcity impact of dairy farming in Punjab.

2.6. Data Analysis

The quantified water-related indicators for dairy farm sheds, *direct blue water use*, *direct blue water consumption*, *indirect blue water consumption*, *total blue water consumption*, *blue water productivity* (WP_{blue}), *and water scarcity footprint* (WSF), were analyzed for their spatial and temporal (annual and seasonal) variability and potential effects of livestock species and farm sizes. An analysis of variance (ANOVA) was conducted to determine differences in the quantified *direct blue water use*, *direct blue water consumption*, *indirect blue water consumption*, and *total blue water consumption*, as per the dairy farm size, type of livestock, and different climatic (rainfall) conditions. A two-dimensional principal components analysis (PCA) was conducted to analyze the blue water use at the studied dairy farm sheds. PCA was employed as a multivariate statistical tool to reduce the dimensionality of the dataset and to identify the key management factors governing blue water use patterns in dairy farm shed operations. The principal components were interpreted based on their factor loadings, with higher absolute loadings indicating stronger influence of specific dairy farm shed factors on blue water consumption. This approach enabled the identification of dominant blue water consumption drivers and simplified the complex relationships among multiple variables into a smaller set of meaningful components. PCA used Kaiser's criterion (eigen value > 1) to identify the most important variables among the various attributes [27]. The Varimax technique was used to produce an orthogonal rotationof the variables in order to produce a correlation between the various activities related to water consumption on the dairy farms.

3. Results and Discussion

3.1. Spatial and Seasonal Variation in Different Blue Water Use Activities

Table 3 presents the quantification of direct and indirect blue water use in different dairy farm shed activities, measured in liters per Adult Animal Unit per day, across different farm types (sizes) in different climatic (rainfall) zones and seasons (summer and winter months) in the study area.

Table 3. Estimates of blue water used and consumed (L water per animal per day) for different dairy farm system activities per season and farm sizes in different climatic zones for the studied farms in Punjab state (India) during the year 2022–2023.

Climatic Zone	**Medium Farms (<25 Dairy Animals)**		**Large Farms (25–100 Dairy Animals)**		**Commercial Farms (>100 Dairy Animals)**	
	Summer (April to October)	**Winter (November to March)**	**Summer (April to October)**	**Winter (November to March)**	**Summer (April to October)**	**Winter (November to March)**
Livestock drinking water (L water consumed per animal per day)						
Medium Rainfall Zone (>400–800 mm per year)	44.56 ± 7.05 ^{aA}	33.43 ± 11.77	48.43 ± 7.38 ^{bB}	28.36 ± 9.13	46.71 ± 12.86 ^{c}	34.37 ± 10.50
Low Rainfall Zone (<400 mm per year)	45.64 ± 16.49	30.07 ± 10.44 ^{aA}	49.80 ± 11.24	37.35 ± 8.43 ^{B}	42.78 ± 9.64	32.06 ± 7.25 ^{cC}
Livestock bathing and servicing (L water used per animal per day)						
Medium Rainfall Zone (>400—800 mm per year)	77.60 ± 17.51 ^{aA}	10.57 ± 1.49	57.22 ± 11.69	8.35 ± 1.98	49.57 ± 13.83	7.63 ± 2.13
Low Rainfall Zone (>400 mm per year)	63.15 ± 17.45	9.65 ± 2.63 ^{a}	57.95 ± 12.64	8.93 ± 1.95	54.23 ± 6.95	8.21 ± 1.00 ^{c}
Indirect water (via energy) consumption (L water consumed per animal per day)						
Medium Rainfall Zone (>400–800 mm per year)	56.32 ± 8.07 ^{a}	41.87 ± 6.03	41.64 ± 8.89	31.00 ± 6.63	31.78 ± 5.60 ^{c}	23.62 ± 4.16
Low Rainfall Zone (<400 mm per year)	53.12 ± 14.24	39.41 ± 10.55 ^{aA}	33.51 ± 8.63	24.92 ± 6.38 ^{b}	47.13 ± 8.11	35.02 ± 6.01 ^{cC}

$^{aA–cC}$ notes in the same row significantly different ($p < 0.05$) mean values.

(i) Dairy livestock drinking water

The livestock drinking water intake showed a clear seasonal pattern, with higher values recorded during summer (April to October) compared to winter (November to March) in both medium and low rainfall zones (Table 3). The average livestock drinking water consumption varied from 42.78 to 49.80 L per adult animal per day in the summer season and from 28.36 to 37.35 L per adult animal per day in the winter season (Table 3). In the summer season, characterized by higher temperatures, the notably higher livestock drinking water consumption could be attributed to the increased hydration demands of bovines. Conversely, the winter season requires reduced drinking water intake due to lower evaporative cooling demands. A statistical analysis confirmed that the average daily livestock drinking water consumption was significantly influenced by the season

($p < 0.001$), showing the decline of 20 to 40% from the summer to winter season (Table 3). However, there appears to be no significant effect of the farm sizes (medium, large, and commercial) on average livestock drinking water consumption patterns in the summer and winter seasons (Table 3).

Our results align with earlier research findings by Bansod [28], who also reported seasonal variations in drinking water intake for lactating crossbred Karan Fries, Tharparkar, and Sahiwal cattle, as well as Murrah buffaloes in Uttar Pradesh (India). Novelli et al. [29] highlighted that dairy cattle increase their drinking water consumption during high temperatures to regulate their body temperature, which explains their higher drinking intake observed during the summer season (Table 3). Sharma et al. [30] also recorded a similar daily drinking water consumption of about 46 L/day and 29 L/day for lactating Murrah buffaloes in the summer and winter seasons, respectively, at Karnal (Haryana, India) in 2014.

However, the dairy livestock drinking water intake values observed in this study (Table 3) were lower than those reported in other studies, such as 70.3 L/day for Holstein Cows at the New Hampshire Agriculture Experiment Station Dairy Sheds (U.S.A.) [31]; 72 L/day for dairy cows in the Waikato region of New Zealand [32]; 77.2 L/day for Holstein Cows in France [33]; and 78.4 L/day for lactating dairy cows in North America, Europe, and Australia [34]. These variations in dairy livestock drinking water may result from differences in climatic conditions, management practices, and animal productivity. Seasonal livestock drinking water requirements are influenced by their productive factors (e.g., milk yield, lactation stage) and environmental variables (e.g., rainfall, temperature, and wind speed). The higher drinking water intake reported in studies from France, New Zealand, and the USA could primarily be due to higher milk yields, favorable temperate climates, and well-managed housing and feeding systems. High-producing Holstein Cows require more water to support greater milk synthesis, while cooler climates reduce heat stress and support optimal metabolic activity. These systems also ensure consistent access to clean water and nutrient-rich diets. In contrast, regions with hotter climates, limited water access, and lower milk-yielding breeds (as in this study) show a lower drinking water intake by dairy livestock (Table 3, [30]). This highlights the need to contextualize livestock water requirements based on local livestock productivity levels and environmental conditions for sustainable dairy water management in different climatic conditions. This research underscores the need to consider regional and seasonal variations in livestock drinking water consumption for the sustainable management of water supplies, particularly in water-scarce regions. Strategies to optimize water use in dairy production systems should account for both environmental and livestock productivity factors to ensure the sustainability and resilience of water supplies in the face of climate variability.

(ii) Dairy livestock bathing and servicing

Livestock bathing and servicing water use, a crucial component for maintaining animal hygiene and cooling, also showed a significant variation between summer and winter seasons in the study area (Table 3). However, there appears to be a similar rate and variation in the daily average livestock bathing and servicing water used in different farm sizes and climatic (rainfall) zones (Table 3).

Table 3 reveals a pronounced seasonal effect on blue water use for livestock bathing and cleaning services at the studied dairy farm sheds. Across all of the studied dairy farm sizes and climatic zones, the average livestock bathing and servicing water use was recorded as being substantially higher in summer than in winter, with approximately five to six times higher numbers in summer. For example, the medium dairy farm sheds in the medium rainfall zone used 77.60 L/animal/day in summer compared to 10.57 L/animal/day in winter, recording about a six-time increase in livestock bathing and servicing water use in the summer. Similarly, at the commercial dairy farm sheds in the medium rainfall zone, the average livestock bathing and servicing water use in summer was estimated to be five times higher at 49.57 L/animal/day compared to 7.63 L/animal/day in winter (Table 3). However, despite this seasonal variability, no statistically significant differences were observed in the average livestock bathing and servicing water uses across different dairy farm size types (medium, large, or commercial) or between low and medium rainfall zones. This indicates that seasonality is the dominant factor influencing livestock bathing-related water use rather than the dairy farm scale or agro-climatic location. These findings underscore the need for season-specific water management strategies, especially during summer, to ensure the provision of a sustainable water supply for livestock bathing and servicing water in dairy farming systems.

Significantly lower livestock bathing and servicing water use in the winter season was due to the decrease in the livestock bathing frequency from twice a day in the summer season to once a week in the winter season. Thomson et al. [35] also assessed the washing water for lactating dairy cattle to be 25 L of water per cattle per day in the United Kingdom. Krauß et al. [36] reported the use of 33.8 L of water per cattle per day for cleaning, when applying high-pressure cleaners and hoses with large diameters on a commercial dairy farm in Northeast Germany from 2012 to 2014. A Canadian study found that 246 L of water per day per cattle was used on average for on-farm activities at dairy farms located in Ontario [8]. Gutierrez et al. [37] reported water use in the range of 55–60 L per cow per day for washing activities on an experimental farm in Uruguayan conditions. However, milking parlor (washing activities) water use averaged 50 L/cow/day, peaking at 82 L/cow/day during the peak lactation months in New Zealand from June 2013 to May 2015 [32]. It appears to be a high variation that is reported in the livestock bathing and servicing water use across dairy farm sheds. However, the use of livestock bathing and servicing water could be greatly influenced by variations in dairy farm types and their management practices and climatic conditions. The importance of the farm workforce (human factor) and daily farm management practices was also emphasized by Jennerich et al. [38] as the variables with the greatest impact on water use on dairy farms in Argentina in 2019-20. This highlights the importance of locally measured datasets and models in the assessment and optimization of the productivity and sustainability of water use in dairy milk production under different farm types and climatic conditions (Table 3).

(iii) Indirect (via energy) water consumption

The major processes of energy consumption were identified as milk cooling, milking, pumping water, lighting, and summer housing systems at the studied dairy farms. In general, the electricity used in the dairy shed accounted for almost 80% of the total energy used, while the rest of the energy was used in the form of diesel consumption for power backup for lighting, ventilation, and washing of the sheds and equipment. On average, the electricity consumed was quantified from 90.3 to 361.0 kwh per month on the medium-size farms, from 451.3 to 722.0 kwh per month on the large-size farms, and from 902.5 to 1805.1 kwh per month on the commercial-size farms. Similarly, the average diesel fuel consumption was quantified from 10 to 20 L per month at the medium-size farms, from 25 to 40 L per month at the large-size farms, and from 50 to 80 L per month at the commercial-size farms. This variation could be attributed to the farm sizes, their energy supply sources, and energy use processes and practices.

Using Equation (4), the indirect blue water consumption, related with the production of energy consumed, was quantified, on average, from 23.62 to 56.32 L of water per animal per day on the studied dairy farms (Table 3). However, the daily average indirect (energy) water consumption (measured as L per animal per day) was found to be variable between the seasons, being quantified at about 25–27% higher in the summer than in the winter season (Table 3). The indirect blue water consumption followed a similar seasonal pattern as the livestock drinking and bathing water consumption, with higher usage in summer and reduced usage in winter.

In the medium rainfall zone, the commercial farms recorded the lowest indirect (embedded in energy) blue water consumption from 31.78 L/day/animal in the summer, decreasing to 23.62 L/day/animal in the winter (Table 3). However, relatively less indirect water consumption was quantified at the commercial and large farms compared to the medium farms (Table 3). This suggests a more efficient use of energy in larger operations at large and commercial dairy farms. However, in the low rainfall zone, the pattern was slightly different, in which the studied commercial farms consumed more indirect water in the summer and winter seasons compared to the large farms. Also, interestingly, the commercial farms located in the low rainfall zone exhibited significantly higher indirect blue water consumption at a rate of 47.13 L/day/animal in the summer compared to their counterparts located in the medium rainfall zone (Table 3). The medium-size farms showed a similar indirect water consumption in the medium and low rainfall zones (Table 3), whereas the large farms recorded relatively less indirect water consumption in the low rainfall zone (Table 3). This variation in indirect water consumption could be greatly influenced by variations in the management of various energy consumption processes, including milking, cooling systems, and other processes, at the studied dairy farms. A relatively higher indirect water consumption for energy use by the commercial farms in the low rainfall zone could reflect the need for more energy-intensive processes in a drier, possibly hotter environment, particularly for cooling and maintaining farm operations.

Overall, the results in Table 3 underscored the influences of seasons (summer and winter months) and different farm types (medium, large, and commercial) on average livestock water use and consumption, both direct and indirect, at the studied farms. The total water used, including for livestock drinking, bathing, and servicing, and indirectly consumed in the form of energy was quantified at 130.83 ± 19.23 L per animal per day on the medium farms, followed by 114.67 ± 14.41 L per animal per day on the large farms, and 111.68 ± 13.52 L per animal per day on the commercial farms. The relatively higher dairy farm shed water use in the summer season (Table 3) suggests higher water demands in relatively drier summer months in the arid and semi-arid regions of the Punjab state. Additionally, differences in dairy livestock water usage between the medium and low rainfall zones (Table 3) reflect potential impacts of climatic conditions on dairy farm water use, with the dairy farm sheds located in the drier low rainfall zone showing slightly higher water usage in commercial farm types, particularly for indirect water consumption in the form of energy used on the studied farms (Table 3).

3.2. Variations in Blue Water Use and Consumption

The records of blue water use at the studied dairy farm sheds (Table 2) were further analyzed, applying Equations (1)–(3), in terms of their direct blue water use and blue water consumption per kg of *FPCM* produced at different types of farms in different climatic (rainfall) zones, as follows:

(i) Direct blue water use

The direct blue water use (Equation (1)) was quantified from 7.09 to 29.15 L of water per kg of *FPCM*, with an average of 14.78 L of water per kg of *FPCM* (Figure 4). As compared to the average direct blue water use (14.78 L/kg *FPCM*), the large- and medium-size study farms had relatively higher direct blue water uses of 16.89 and 16.23 L/kg *FPCM*, respectively, while the commercial farms had a significantly lower direct blue water use of 11.23 L/kg *FPCM* (Figure 4). This variation in direct blue water use across the studied farms may be attributed to differences in their livestock water management activities (Table 3) and differences in their average milk yields (Table 1). The commercial farms had slightly more high milk yielding animals in the medium rainfall zone (Table 1).

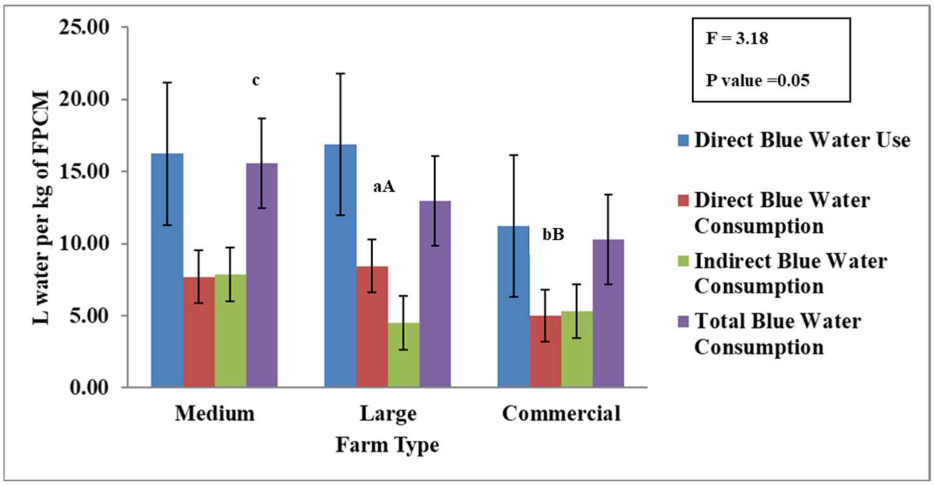

Figure 4. Estimates of direct and indirect blue water usage and consumption (*L per kg of FPCM)* of different dairy farm sizes studied across Punjab state (India) during the year 2022–2023. The medium farm represents <25 dairy livestock per farm, large represents 25–100 dairy livestock per farm, and commercial represents >100 dairy livestock per farm. $^{a–c}$ and ^{A,B} Means in the different blue water footprints in different dairy production systems with superscripts are significantly different ($p < 0.05$).

However, direct blue water use accounts for livestock bathing and dairy shed servicing, which is returned as effluent discharges. From a water footprint perspective, not considering the gray (water quality) footprint, blue water consumption accounts for the water consumed only, as the effluent discharge is considered as a return water flow [19]. This is further analyzed as direct blue water consumption of the studied dairy farms, as follows.

(ii) Direct blue water consumption

The direct blue water consumption, which is a measure of the quantity of blue water consumed per kg of *FPCM* (Equation (2)), was calculated from 3.33 to 13.56 with an average of 7.05 L/kg of *FPCM* (Figure 4). Farm-wise analysis quantified that the average direct blue water consumption was relatively higher (8.45 to 7.69 L/kg of *FPCM*) in the large and medium farms, as compared to the commercial farms (5 L/kg of FPCM). A relatively lower than average direct blue water consumption at the commercial farms (Figure 4) could be partially attributed to the higher milk yield of their dairy livestock, especially in the medium rainfall zones (Table 1).

Ibidhi and Saleh [39] also reported a similar direct blue water consumption (accounting for livestock drinking water) of 5.14 L per kg of *FPCM* produced in Tunisia during 2018. Owusu Sekyre et al. [40] also reported a similar direct blue water consumption in livestock drinking activities of 6.32 L per kg of *FPCM* produced in South Africa in 2015. In similar studies in India, Singh et al. [41] and Singh and Singh [42] reported direct blue water consumption by livestock drinking in the range of 8.71–10.42 and 26.71–46.74 L per kg of *FPCM* produced in Bihar and Eastern U.P. (India). In this study, the average direct blue water consumption of 7.05 L/kg of *FPCM* (Figure 4) was quantified as being relatively slightly lower compared to other Indian studies [41,43].

However, the average direct blue water consumption (7.05 L/kg of *FPCM*) was quantified as being relatively much lower than the average direct blue water use (14.78 L/kg of *FPCM*) (Table 3 and Figure 4). This suggests that >50% of the direct blue water used is not actually consumed but discharged as effluent in the studied dairy farms. This highlights the potential scope of the robust management of effluent discharges and their recycling in dairy sheds to help reduce the gray (water quality) and blue water use on the dairy farms in the study area. On a New Zealand dairy farm, Bowler & Longhurst [44] reported a reduction of more than 50% in average dairy shed water use, from the industry benchmark of 70 L/cow/day to 30 L/cow/day, by using recycling-treated effluent for washing down the dairy stock holding yards over two lactations (2016/2017 and 2017/2018).

(iii) Total blue water consumption, including direct and indirect blue water consumption

Using Equation (3), the indirect blue water consumption, associated with energy (electricity and diesel) consumption, was quantified from 3.18 to 13.29 with an average of 5.88 L per kg of *FPCM* (Figure 4). However, the average indirect blue water consumption was quantified relatively higher in the medium (7.86 L/kg of *FPCM*) and commercial (5.30 L/kg of *FPCM*) dairy farm sheds, as compared to the large (4.49 L/kg of *FPCM*) dairy farm sheds (Figure 4). This variation in indirect blue water consumption across the studied dairy farms may be attributed to variations in the management of energy consuming infrastructure/equipment affecting the variability in their energy consumption, sources of energy supplies (electricity vs. diesel consumption), and average milk yields at different types of study farms. However, this study is the first globally to quantify the energy-related indirect blue water consumption of dairy farm sheds using primary records of on-farm energy use data in semi-arid regions. It offers a novel, disaggregated benchmark for total blue water consumption in tropical dairy systems, going beyond existing aggregated global estimates.

The total blue water consumption, sum of the direct blue water consumption and indirect blue water consumption, varied from 10.30 to 15.55, with an average of 12.93 L/kg of *FPCM* for the studied dairy farms (Figure 4). Interestingly, a large share of the average total blue water consumption was contributed by indirect blue water consumption, which accounted for 45% of the average total blue water consumption on the studied dairy farms. This highlights a significant scope for reducing dairy milk production water footprints by focusing on improving both water and energy usages in the operation and management of dairy farm sheds in the study area.

3.3. Management Practices Influencing Blue Water Consumption

The PCA reduced the studied dairy farm sheds' data dimensionality and identified distinct components reflecting underlying key dairy farm-level management practices affecting their total blue water consumption per unit of milk produced. The PCA component matrix extracted four interpretable components, each representing a coherent cluster of interrelated variables (see Table 4).

PCA component 1 exhibited high positive loadings for livestock *bathing* (0.71), *drinking* (0.58), dairy shed *energy* (0.57), and % *buffalo* (0.69), and a strong negative loading for *crossbred cattle* (−0.67). The daily average blue water usage (L per adult animal per day) was also quantified to be variable for different livestock species, varying from 71 ± 22 for crossbred cattle, 32 ± 19 for indigenous cattle, and 82 ± 27 for buffalo on a commercial farm (Figure 5). This configuration suggests a dairy system where buffalo-based dairying is strongly associated with higher water and energy use but has a lesser per animal total blue water consumption due to a higher *FPCM* yield. The bathing of animals, which is more frequent for buffaloes due to their lower heat tolerance, and the higher energy requirement for cooling and mechanization are prominent in this cluster. This finding aligns with earlier studies from India and abroad. Pandey and Sirohi [45] reported that buffalo-based dairy milk production systems in North India required significantly more blue water per liter of milk compared to crossbred cattle systems. Similarly, Farooq and Shahid [7] confirmed that buffaloes require more frequent bathing for climate control, especially in the hot, semi-arid conditions of Pakistan.

Table 4. Scores of principal component analysis of dairy livestock species effect on blue water consumption in different activities at the studied dairy farms in Punjab state (India) during the year 2022–2023.

Component Matrix				
Variables	**Component**			
	1	**2**	**3**	**4**
Bathing	0.71	0.50	0.19	
Drinking	0.58	0.42	0.51	0.10
Energy	0.57	0.54	−0.29	
Buffalo (%)	0.69	−0.72		
Crossbred Cattle (%)	−0.67	0.68	0.16	−0.23
Servicing	−0.21	−0.33	0.77	0.32
Indigenous Cattle (%)	−0.17	0.18	−0.33	0.91

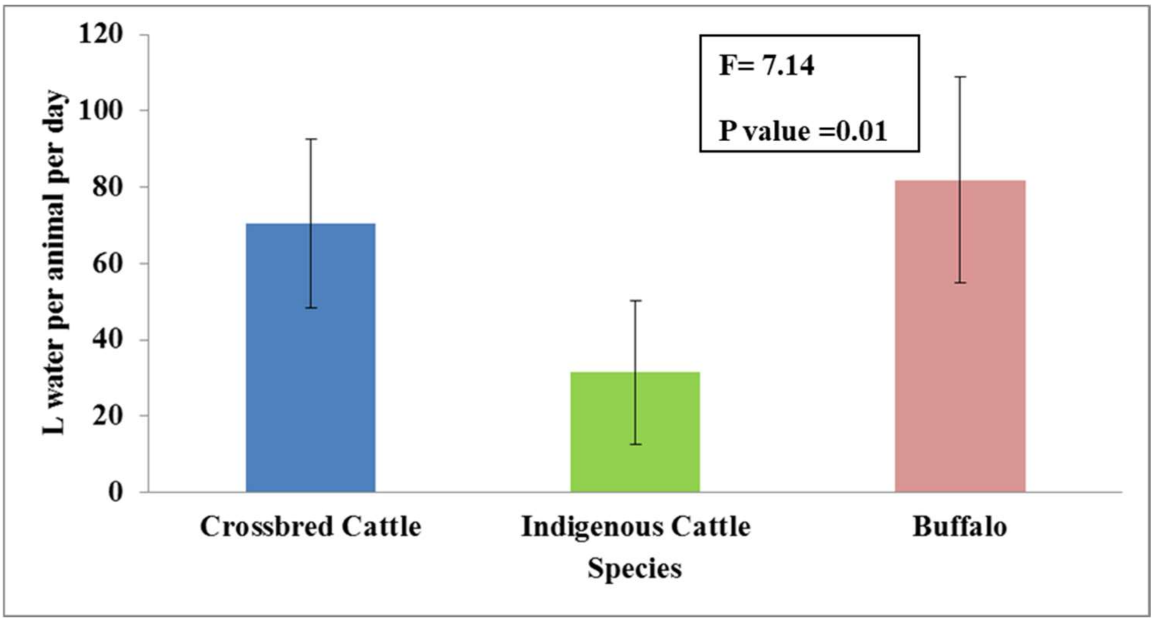

Figure 5. Average daily blue water utilization by different dairy livestock species on a commercial farm in Punjab state (India). It is based on the daily water flow meter recordings on the farm from July 2022 to June 2023.

PCA component 2 was defined by contrasting loadings for % *buffalo* (−0.72) and % *crossbred cattle* (0.68), with moderate loadings on dairy shed *energy* (0.54) and livestock *bathing* (0.50). This component reflects the structural duality between buffalo-centric and crossbred cattle-centric dairy production systems, each with distinct technological and resource use footprints. While buffalo-based dairy production systems tend to be more traditional, crossbred cattle systems are typically associated with commercialized, high input dairy operations. Comparable dualities have been reported in international studies. However, although buffalo-based systems tend to have higher water use per animal, their *FPCM* yields result in lower blue water consumption per unit of *FCPM* output compared to the crossbred systems. This finding is consistent with broader water footprint studies, which indicate that well-managed buffalo-dominated dairy production systems can achieve higher dairy milk blue water productivity despite greater per-animal resource use. Consequently, component 2 reflects a system-level trade-off: buffalo-based dairy systems are more water- and energy-intensive at the animal level but more efficient in converting blue water into *FPCM*. The crossbred cattle-based dairy systems generally involve higher servicing water and infrastructure inputs with comparatively lower per-animal productivity. This pattern aligns with trends reported in both Indian and international water footprint analyses [39,42].

PCA component 3 was dominated by a strong loading for dairy shed *servicing* (0.77), along with a moderate association with livestock *drinking* (0.51). This component represents management-intensive systems, where the regular washing and cleaning of floor and dairy equipment are prevalent. The dairy shed's service water intensity, particularly for water used for cleaning the sheds and maintaining hygiene, may be indirectly associated with higher dairy productivity, as it reflects improved farm management and animal care practices. Earlier studies using multivariate analyses have shown that more intensively managed dairy farms, characterized by better maintenance and operational inputs, tend to achieve higher milk yields [46].

The final PCA component, component 4, showed a very strong loading for % *indigenous cattle* (0.91), while other variables loaded weakly. This component likely captures low-input, traditional dairy systems, which rely on native breeds. These systems are characterized by minimal servicing, lower energy needs, and better adaptation to local environmental conditions. However, they often exhibit lower milk productivity compared to commercialized systems. These findings are consistent with international research emphasizing the resilience of indigenous breeds. Singh and Singh [42] highlighted that native breeds are essential for maintaining system-level sustainability and that, despite lower milk yields, indigenous breeds are vital for climate-resilient dairying, particularly in marginal areas with limited input access.

3.4. Blue Water Productivity Across Dairy Farm Types

The dairy milk blue water productivity, expressed as kg *FPCM* per m^3 of blue water consumed (Equation (4)), varied considerably across dairy livestock species and farm sizes, reflecting the combined influence of dairy animal productivity and resource use efficiency (Figure 6). Across all farm categories, buffalo-based dairy milk production demonstrated the highest blue water productivity, ranging from 153.87 ± 11.20 kg *FPCM per* m^3 of blue water consumed in the studied medium farms to 224.46 ± 58.53 kg *FPCM per* m^3 of blue water consumed in the studied commercial farms. This superior performance by buffalo-based dairy milk production aligns with findings from North Gujarat (India), where water productivity for buffalo milk was reported around 310 kg *FPCM per* m^3 of water, attributable to their higher milk solids content and better conversion efficiency under well-managed conditions [46]. Crossbred cattle also exhibited relatively higher dairy milk blue water productivity, ranging from 190.36 to 132.62 kg *FPCM* per m^3 of blue water consumed (Figure 6). This is consistent with their improved genetics, adaptability to semi-intensive production systems, and greater adoption of scientific feeding practices, as supported by comparable figures in global assessments [47]. Indigenous cattle showed the lowest dairy milk blue water productivity, ranging from 97.12 to 56.35 kg *FPCM* per m^3 of blue water consumed (Figure 6), reflecting their lower milk yields and limited use of intensified management practices, a pattern observed in various international dairy studies.

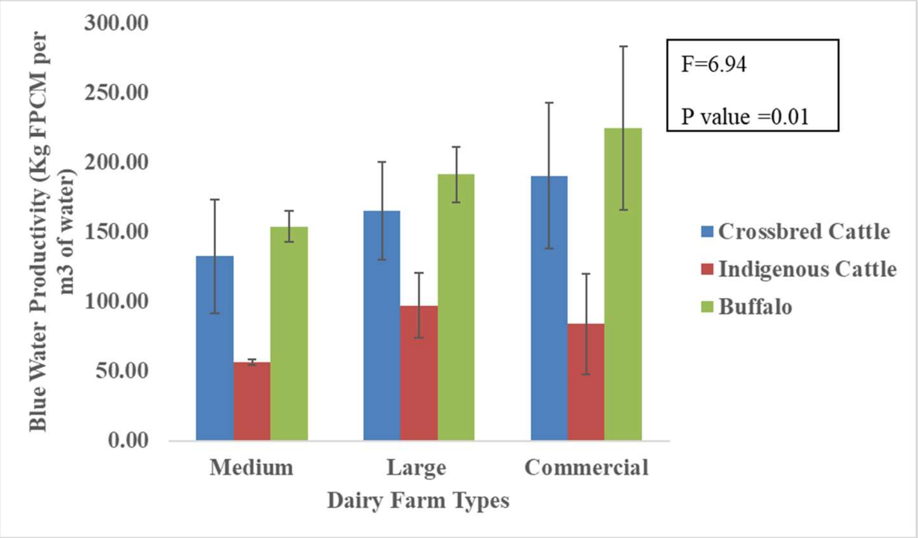

Figure 6. Variation in dairy milk blue water productivity (kg FPCM/m^3 of blue water consumed) of crossbred cattle, indigenous cattle, and buffalo livestock species under different dairy farming sizes studied across Punjab state (India) during the year 2022–2023. The medium farm represents <25 dairy livestock per farm, large represents 25–100 dairy livestock per farm, and commercial represents >100 dairy livestock per farm.

Farm typology exerted a significant influence on quantified dairy milk blue water productivity, with the studied commercial dairy farms outperforming the studied large- and medium-scale dairy farms, except for the indigenous cattle farms (Figure 6). The superior dairy milk blue water productivity on the studied commercial dairy farms is likely a result of comprehensive resource management, optimized feed–water integration, and more efficient water use infrastructures such as controlled watering points. The studied large-size dairy farms displayed an intermediate daily milk blue water productivity performance, indicating the partial adoption of improved practices, whereas the medium-size farms lagged, reflecting suboptimal water use infrastructure and production inefficiencies.

It is worth noting that the dairy milk blue water productivity quantified in Figure 6 only accounts for drinking water directly consumed by livestock and the indirect blue water consumed via energy but excludes any blue and green water consumed for the production of dairy livestock feed at the studied dairy farms. However, accounting for dairy livestock feed water consumption is expected to result in lower dairy milk water productivity values at the studied dairy farm sheds. In Southern Brazil and Germany, intensive, well-managed dairy systems demonstrated improved water productivity, reaching up to 1.7 kg *FPCM* per m^3 of water consumed in high-yielding commercial operations, when feed-related water use was included in the calculation of water productivity [21,36].

However, Figure 6 underscored robust management variations on the performance of dairy livestock milk yields and dairy farm blue water and energy use management practices as critical determinants of dairy milk blue water productivity. This is congruent with analyses across diverse agroecological zones such as the USA, where dairy milk water productivity increased nearly fivefold since 1960 due to improved dairy livestock genetics and farm management practices [48]. In conclusion, these findings corroborate extensive research demonstrating that dairy livestock species selection, farm management intensity, and farm infrastructure substantially affect dairy milk water productivity in dairy production systems. Targeted interventions to improve dairy farm management and technology uptake, especially in medium and large farms, promise considerable gains in improving the productivity and sustainability of dairy milk production in water-limited, semi-arid regions like the study area.

3.5. Assessment of Dairy Farm Sheds' Water Scarcity Footprints in Punjab State

Punjab is a leading agrarian state of India contributing significantly to the food security of the country. However, in recent years, because of the overdrafting of groundwater for irrigation purposes for rice, the state is witnessing a severe decline in the water table. Annually, 28.01 Billion Cubic Meters (BCMs) of groundwater are drafted against the available groundwater of 17.07 BCM, which is around 164% overdrafting of groundwater, rendering contemporary levels of groundwater use highly unsustainable in the Punjab state [14]. Further, about 95 percent of groundwater extraction is utilized for agricultural irrigation purposes, while industrial and domestic usage constitutes roughly 5 percent [14]. As domestic groundwater pumping is being used as the primary water source for dairy operations in the Punjab state [49], the total direct blue water use of dairy farming shed operations in the selected districts during the study period 2022–2023 was estimated at 36.72 Million Cubic Meters (MCMs) (Table 5). However, dairy farming sheds in the state are estimated to be utilizing around 8.28 percent of the groundwater usage for domestic (other than irrigation and industrial) purposes in the Punjab state (Table 5).

Table 5. Assessment of groundwater use in dairy farming in Punjab-based quantification of blue water use at 24 dairy farms in Punjab state (India) during the year 2022–2023.

Zone	Districts	Groundwater Over Utilization (%)	Groundwater Usage Other than Irrigation and Industrial Level (MCM)	Estimates of Direct Blue Water Usage in Dairy Farming Shed Operations (MCM) *	% of Groundwater Usage
Medium Rainfall Zone (>400–800 mm per year)	Ludhiana	215	149.39	8.89	5.95
	Jalandhar	207	134.45	5.39	4.01
	Amritsar	179	63.6	7.73	12.16
	Fatehgarh Sahib	207	25.18	2.67	10.61
Low Rainfall Zone (<400 mm per year)	Mansa	125	32.27	4.09	12.68
	Muktsar	25	37.89	2.76	7.30
	Faridkot	147	25.94	2.64	10.20
	Bathinda	116	58.3	5.41	9.28
Punjab		164.11	1169.67	96.83	8.28

Notes: * The direct blue water use for livestock dairy farming sheds in the selected districts was calculated by multiplying the estimates of daily blue water use per animal by the total livestock population in each respective district.

However, the current estimates of the direct blue water use of dairy farming sheds' operations in Punjab are estimated as being relatively much lower compared to the share of groundwater used for agriculture. For example, on average, one kg of *FPCM* required 11.81 L of direct blue water consumption (Figure 4), while one kilogram of rice production required 2053 L of groundwater for irrigation (Srivastava et al., 2015 [5]). It is worth noting that the direct blue water consumption quantified for dairy farming sheds' operations in this study did not account for indirect blue and green water consumption in terms of feed and fodder used for feeding dairy livestock on the dairy farms studied. However, the biophysical, economical, and nutritional water productivities of crops (e.g., rice) and dairy milk production are expected to be different [50] and require further assessment for optimizing the productivity and sustainability of water use in agricultural production in the study area.

The spatial variation in the district-wise dairy farming sheds' water scarcity footprints (*WSFs*) analysis (Figure 7) adds an important layer of robust assessment of dairy farming water impacts on Punjab's broader groundwater crisis. The *WSF* results showed that even modest dairy sheds' operational blue water consumption exerts relatively higher water scarcity impacts when it occurs in the districts already facing acute groundwater depletion. This is particularly evident in districts such as Ludhiana, Amritsar, and Bathinda, where dairy farming sheds' *WSF* values are quantified as being significantly higher than in other districts such as Muktsar and Faridkot. The Ludhiana, Amritsar, and Bathinda districts not only host large dairy livestock populations but are also located in regions with critically over-exploited aquifer conditions, under which every additional cubic meter of groundwater use intensifies water scarcity pressures in the districts.

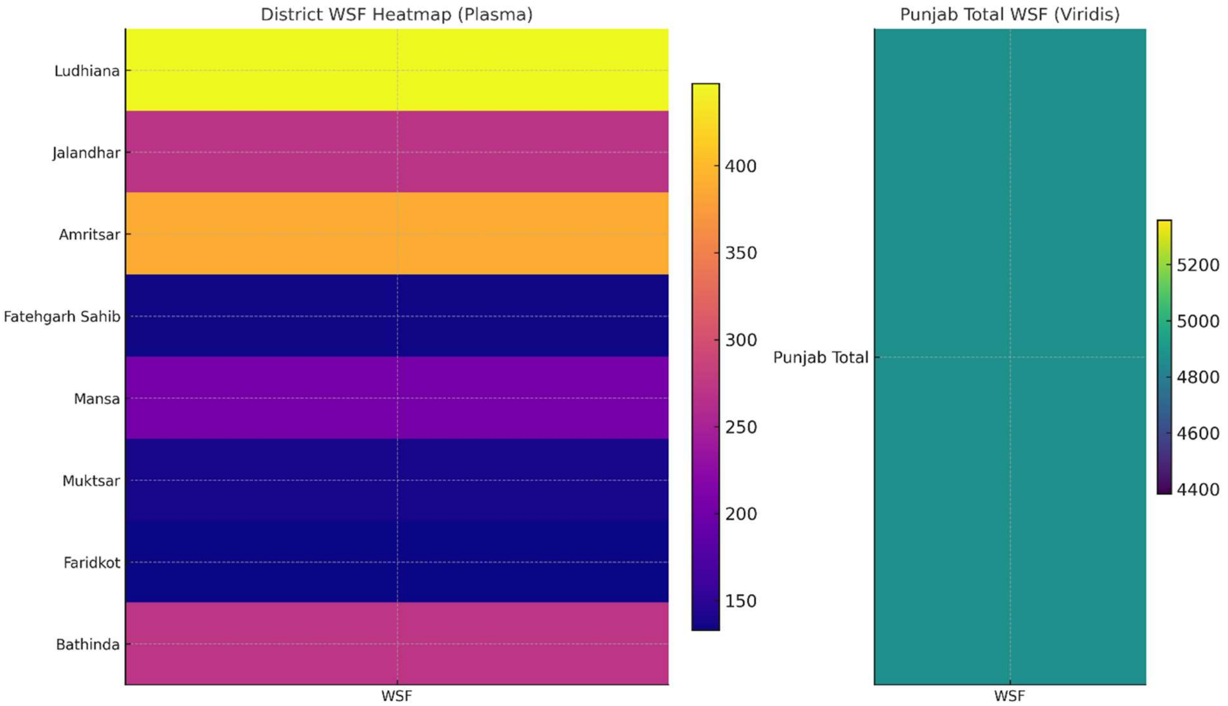

Figure 7. Estimates of dairy production-related water scarcity footprint (*WSF*) (million m^3 world-eq.) of different dairy farms studied across Punjab state (India) during the year 2022–2023. The left panel presents district-wise *WSF* values using the Plasma color scale to highlight spatial variation across districts, while the right panel uses the Viridis scale to represent the aggregated Punjab *WSF*. The *WSF* values were calculated using the AWARE non-agricultural characterization factor (50.3 m^3 world-eq per m^3), based on operational (non-irrigation) dairy water use. Brighter colors indicate higher scarcity impacts.

This pattern underscores a critical insight: the dairy farming sheds' *WSFs* are not merely a function of how much blue water is consumed in dairy farm operations but where that water is consumed. For example, the relatively higher dairy *WSF* in Ludhiana and Amritsar reflects the interaction between higher dairy sector water consumption and extreme groundwater overdraft (far exceeding 200% in several blocks). Thus, even though dairy farming accounts for only about 8.28% of the total domestic water use in Punjab, its water scarcity impacts are magnified in hydrogeologically vulnerable districts.

In contrast, districts such as Faridkot and Muktsar, which exhibit comparatively lower dairy *WSF* values due to the consumption of less blue water in dairy farming sheds' operations and being situated in relatively less-stressed aquifer zones. This differentiation is crucial for regional water management across the different districts of the study area. However, the aggregated dairy sector *WSF* at the state level resulted in a cumulative value of 4870 million m^3 world-eq, but the heatmap demonstrates that the burden is far from uniform across the state (Figure 7).

Comparative international studies reinforce the spatial variability patterns observed in Punjab's district-wise dairy *WSF* analysis. Both the New Zealand study by Payen et al. [51]

and the Taiwan study by Liao & Su [52] highlighted how modest operational water use amplifies water impacts in hydrogeologically stressed regions. Payen et al. (2018) [51], in New Zealand, reported a 50× disparity (22 L world eq/kg FPCM in low-stress Waikato vs. 1118 world eq/kg FPCM in irrigated Canterbury), and Liao & Su (2019) [52], in Taiwan, revealed extreme northern/central hot spots (44.8 water eq/kg FPCM, $WSI \approx 1$). This aligns with Punjab's elevated *WSF* in over-exploited Ludhiana/Amritsar/Bathinda (>200% aquifer overdraft) over less-stressed Muktsar/Faridkot, despite dairy farming shed operations accounting for only 8.28% of the domestic water share. However, a high-resolution analysis of *WSF*, highlighting the hot spot districts in Punjab, further guides the potential for relocation or focus on dairy farming sheds' operations to low-*WSI* zones, informing targeted Punjab policies amid groundwater crises.

The combined analysis of dairy milk water productivity (*WP*) and water scarcity footprint (*WSF)* results strengthen the argument that Punjab's water sustainability challenges call for spatially differentiated interventions targeting low dairy *WP* systems and high dairy *WSF* districts for stricter groundwater regulation and improved dairy water use efficiency, while monitoring lower dairy *WSF* districts to prevent future over-extraction. This spatially nuanced approach becomes especially important given the region's heavy dependence on groundwater. Also, the exclusion of indirect (feed-related) dairy water use from the current dairy direct blue water consumption estimates in this study suggests that the true water burden of dairy farming is higher than what dairy farming sheds' operational data alone indicate in this study.

3.6. Policy Implications for Sustainable Water Use in Dairy Farming

The findings of this study have important implications for improving the productivity and sustainability of water use in dairy farming systems, particularly in arid and semi-arid regions. Given the observed variations in blue water use and consumption across different farm sizes, livestock types, and seasons, targeted interventions are required to optimize daily milk blue water productivity and reduce the water scarcity footprint. Adoption of water-efficient management practices, such as improved livestock bathing systems, controlled water dispensing, and the recycling of wastewater for cleaning purposes, can significantly reduce direct blue water consumption in dairy farm shed operations. Additionally, promoting water-saving technologies in dairy shed operations, including efficient cooling and cleaning systems, can help minimize the operational water use of dairy milk production. Similarly, energy-saving technologies and alternative sources of energy (with a lower water footprint) can significantly help minimize the indirect water consumption of dairy milk production in the study area.

From a policy perspective, there is a need to encourage resource-efficient dairy production systems through incentives, subsidies, or awareness programs that support farmers in adopting sustainable practices. Strengthening local data monitoring systems and region-specific water use benchmarks can further assist in improving decision-making at both farmer and policy levels. Furthermore, integrating water productivity and water footprint assessments into dairy development programs can help align productivity goals with environmental sustainability in the livestock sector.

3.7. Limitation of the Study

This study was conducted on a total of 24 dairy farm sheds across the groundwater-depleted state of Punjab, and the findings are therefore highly relevant and can be generalized to similar agro-climatic regions facing groundwater scarcity. However, the farm sample size remains somewhat limited for broader generalization across diverse dairy production systems and geographical regions. Additionally, the dairy farming water use analysis in this study focuses on direct blue water use and indirect blue water consumption in the form of energy consumed at the studied dairy farm sheds. This study did not include accounting for the blue and green water consumption associated with dairy livestock feed production, which could be incorporated in future studies for a more comprehensive assessment of dairy milk water productivity and the water scarcity footprint in the study region and other similar climatic conditions.

4. Conclusions

The study results offer valuable insights into the complex spatial and seasonal dynamics of blue water use, direct and indirect blue water consumption, blue water productivity, and water scarcity footprints of dairy farming sheds across the Punjab state. The dairy systems' blue water consumption varied significantly, influenced by factors such as climatic seasonality, farm size, and their livestock species. Livestock drinking water intake, particularly during the hot summer season, emerged as a major contributor to overall dairy water usage, with variations observed between different climatic (rainfall) zones and farm sizes (medium, large, and commercial). Additionally, livestock bathing and servicing significantly contributed to direct blue water use, emphasizing the need for targeted interventions to reduce water-intensive practices. However, about 50% of direct blue water use is estimated to be non-consumptive, highlighting the potential for dairy farm effluent treatment and reuse to green wash dairy farm sheds.

Moreover, the assessment of water-related indicators elucidates the importance of considering both direct and indirect water consumption in dairy farming. While direct blue water consumption varied across the studied dairy farming systems, their indirect blue water consumption via energy (electricity and diesel) showed notable variations across different farm sizes, with commercial farms often exhibiting lower indirect blue water consumption per unit of milk *FCPM* produced. About 45% of the total blue water consumption was estimated as indirect blue water consumption via energy (electricity and diesel) consumed by the dairy farming systems. This highlights the potential scope of reducing dairy farming blue water consumption by improving their energy consumption and sources with lower blue water consumption like solar energy supplies. Seasonal impacts further emphasized the importance of adaptive strategies like the promotion of heat-tolerant indigenous breeds, reuse of bathing water for cleaning purposes, etc., to optimize blue water and energy usage efficiency, particularly during hotter summer seasons.

Overall, dairy farming systems based on buffalo and crossbred cattle exhibited higher blue water productivity (up to ~220 kg *FPCM* per m^3 of blue water) compared to the indigenous cattle-based dairy systems. This difference can be attributed to relatively higher milk yields and the adoption of improved management practices in these systems, whereas indigenous cattle-based farms are often characterized by lower productivity and limited intensification. In addition, larger commercial dairy farms demonstrated greater dairy milk blue water productivity than the medium-scale operations, indicating the potential benefits of improved resource management and operational efficiency at scale.

Furthermore, the spatial variation in the water scarcity footprint highlighted the broader implications of dairy farming sheds' operations on Punjab's groundwater resources. While the current water scarcity footprint of dairy farming sheds is relatively lower compared to other groundwater use activities, improving their productivity and sustainability warrants tailored and adaptive management practices, especially in districts facing higher groundwater stress like Ludhiana and Amritsar in the Punjab state. However, further research on indirect feed-related dairy green water and blue water consumption and its water scarcity footprint is recommended to be combined with this study's results to help manage the true water burden of dairy farming in Punjab and similar semi-arid and arid regions.

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