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Review

Review of Water Use Assessment in Livestock Production Systems and Supply Chains †

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Abstract

Improving the water productivity and sustainability of global food supplies and reducing water stress worldwide requires a comprehensive and consistent assessment of water use in global food production systems, including livestock production and supply chains. Presented here is a systematic review of relevant livestock water use studies, published over two periods: "Period 1993–2017" and "Period 2018–2024", assessing consistency in their approaches and identifying opportunities for advancing and harmonizing the assessment of livestock water use worldwide. However, the review highlights that a comprehensive and consistent assessment of livestock water use remains a challenge. The reviewed studies (a total of 317) differ in terms of their accounting of different water flows, setting the system boundaries, and quantification of water productivity and impact metrics. This makes it difficult to compare potential water productivity and environmental impacts of livestock production systems at different scales and locations. Case studies are required to further develop and implement a robust and consistent methodological approach, based on locally calibrated models and databases, of different livestock production systems in different agroclimatic conditions. Also, further communication and training are required to help build the capability to apply a comprehensive and consistent assessment of livestock water use locally and globally. The adoption of a scientifically robust and practically applicable methodological framework will support researchers, policy managers, farmers, and business leaders in sound decision-making to improve the productivity and sustainability of water use in livestock production systems locally and globally.

Keywords: agriculture water use; water scarcity footprint; water productivity; livestock production systems; water sustainability; environmental impact

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1. Introduction

1.1. Context

Around the world, land and water resources are increasingly strained, showing signs of water scarcity, water contamination, and land quality degradation as they support food production—including livestock—to maintain global food security. Agriculture and livestock production are the largest water users, requiring nearly 72 percent of global water withdrawals [1]. However, agricultural water demand is predicted to rise significantly in the future. According to the FAO forecasts, food, feed, and biofuel production will need to increase by 50 percent from 2012 levels by 2050 to meet the demands of a projected global population of 9.7 billion people [2]. On the other hand, intensifying drought conditions, amplified by changing climate conditions, are generating severe water shortages [3]. Increasing water shortages pose heightened risks to global food security and potential for civil unrest in the medium- to long-term [3].

However, reducing risks to global food security and alleviating water stress necessitates comprehensive assessment and significant advances in improving productivity and sustainable utilization of water resources in agricultural production systems, including livestock production systems and supply chains [4]. This requires the development and application of widely recognized, consistent methodological frameworks and guidelines to quantify and assess different water flows and their productivity and environmental impacts in agricultural production systems. However, national and international studies provide different interpretations and uses of the terms “water use efficiency” and “water productivity” [4,5]. Various sustainability-related scientific disciplines use the terms interchangeably or reciprocally as “water productivity” [6]. According to an engineering-dominated understanding, the water use efficiency is the utilization rate of a certain degree of direct water input [6]. However, in livestock production systems and supply chains, multiple direct and indirect water inputs and outputs occur at three interconnected stages: feed crop and pasture production, animal husbandry, and primary processing of livestock products [4].

The livestock feed and pasture production are a relevant part of the agricultural systems across the world, and they are a critical part of livestock production systems and supply chains. A robust assessment of water use in processes like feed production accounts for all water flows entering and leaving the defined system boundaries. Different methodologies have traditionally guided assessment of water use through established indicators and guidelines [6–8]. Following the ISO 14046 standard, the Water Footprint Inventory should include one or more pieces of information pertaining to water flows: (1) the volume of water consumed or degraded; (2) the source type (precipitation, surface, and groundwater); (3) the water flow as an input into the production system or emission(s) to air, soil, and water; and (4) the relevant time frame and geographic location. Water use results are typically expressed as ratios relative to the main output of the process—for instance, liters of water consumed per ton of grain produced in feed production systems.

However, farmers, water managers, and policy makers are increasingly seeking sound knowledge and tools to better quantify different components of direct and indirect water flows and improve the water productivity and environmental performance of agricultural production systems. Until now, the use of different definitions of water use metrics makes it difficult to compare potential water productivity and environmental impacts of different livestock production systems in different studies [9]. This results in a big challenge in communication.

1.2. Importance of Harmonizing Water Use Assessment in Livestock Production Systems and Supply Chains

The scientific community and water managers broadly accept the need to apply a scientifically robust, comprehensive, and consistent assessment of water use in agricultural production systems. A toolkit of the utmost importance for assessing water use in livestock is provided by the “Guidelines for the evaluation of water use of livestock production systems and supply chains” [4,10], developed by the Technical Advisory Group (TAG) for water use of the LEAP (Livestock Environmental Assessment and Performance) Partnership of the Food and Agriculture Organization (FAO). These guidelines [4] suggest the quantification and assessment of the combined water metrics from the following two methodologies, “water scarcity footprint (WSF)” and “water productivity (WP)”, the reciprocal of the water footprint metric defined in the water footprint assessment manual [7]. The FAO LEAP water TAG guidelines [4] aim to provide a scientifically robust framework for the assessment of water use in livestock production systems and supply chains. A combined analysis of both WSF and WP could offer a comprehensive assessment and help identify hot-spots for potential improvements in water productivity and reduction in water scarcity impacts of livestock production systems.

However, harmonization of methodological approaches for the assessment of water use in livestock production systems and supply chains has not yet been achieved, even though the FAO LEAP water TAG guidelines were published back in 2018.

This article presents a systematic review of the existing livestock water use studies, assessing the consistency in their approaches and identifying opportunities for advancing and harmonizing the assessment of water use in livestock production systems and supply chains worldwide. The review focused on two distinct periods, relevant studies published before and after the year 2018, marked as a pivotal year by the publication of the FAO LEAP water TAG guidelines [4]. Relevant studies were systematically collated and reviewed in terms of their focus, study objectives, water use assessment approaches, accounting of different water flows, the study system boundaries defined, and the use of various data sources. The review offers a robust discussion, highlighting key consistencies or inconsistencies among existing studies, and makes recommendations for improving consistency in the assessment of livestock water use. Findings from the literature reviews will contribute to the refinement and uptake of unified, scientifically robust, and practically feasible frameworks for water use assessment of livestock production systems and supply chains worldwide.

2. Review of Livestock Water Use Assessment Studies

2.1. Defintions and Guidelines

Assessment of livestock water use involves considering both direct and indirect water use at three interconnected stages: feed crop and pasture production, animal husbandry, and primary processing of livestock products [4]. Direct water use (foreground) encompasses water use that falls under the direct control or management of the study's focal system. For instance, in a farm-level study, direct water accounts for all on-farm water consumption, while indirect water accounts for water use occurring outside (background) of the study's focal system, such as water consumed throughout the supply chains of purchased inputs, materials, and services [4]. Similarly, in a dairy processing study example, direct water use accounts for all direct water consumed in the processing-plant facility operations, while indirect water accounts for water use occurring in the supply of materials and services, e.g., electricity to the processing plant [11]. A glossary defining important water flows and terms used in the article is provided in Table A1 in Appendix A.1. This glossary also distinguishes the definitions of terms such as "water withdrawal", "water withdrawal (only consumption)", and "water consumption". The term "water withdrawal" refers to the anthropogenic extraction of water from water bodies or drainage basins, encompassing both permanent and temporary removal processes, while the term "water withdrawal (consumption only)" refers to the proportion of water withdrawn that is consumed. The term "water consumption" includes evaporation, transpiration, product integration, or release to alternative drainage basins or oceanic systems. Land-use change impacts on evaporation rates, exemplified by reservoir development, constitute water consumption.

A robust assessment of livestock water use requires a sound understanding and quantification of different direct and indirect water flows in a livestock production system. As per the ISO 14046 standard [8], the "water scarcity footprint" is specifically linked to water consumptive use, while the "water availability footprint" refers to both water consumptive use and water degradative use. Boulay et al. [12] recommended the water scarcity footprint method out of collaborations in the Water Use in LCA (WULCA) working group of the Life Cycle Initiative. However, other studies [13–17] developed and applied the water productivity metrics as a measure of the potential productivity of water use in agricultural production systems, including livestock. The "water productivity (WP)" metric was incorporated in the FAO LEAP water TAG guidelines [4] as per the water footprint assessment manual [7]. The WP is defined as the ratio of the output to the amount of water input (consumed) to produce the output in a production process [5]. The FAO LEAP water TAG guidelines [4] offered a first-time consensus among life-cycle assessment [8] and water footprint assessment [7] approaches to quantify and assess water productivity and its potential water scarcity impacts in livestock production systems [4,5]. Numerous case studies were carried out to present, apply, and validate them for diverse livestock production systems and supply chains; for example, Carra et al. [18] and Palhares et al. [19] published in a Special Issue of the Water journal titled "Assessment of Water Use in Livestock Production Systems and Supply Chains".

However, a comprehensive and consistent assessment of water use in livestock production systems is a developing science in terms of its methods and tools used, the scope and scale of the analysis conducted, and uncertainties in different sources of relevant data available worldwide.

2.2. Materials and Methods

The literature review aimed to give insights into the development and application of water use assessment in livestock production over the last two decades, from 1993 to 2024 (Figure 1). The most important historical events in the field of "assessment of water use" are marked by the publications of Water Footprint Assessment Manual in 2011 [7], the ISO 14046 standard in 2016 and the recommendations of the WULCA-working group to the Life Cycle Initiative in 2017–2018 [12], and the FAO LEAP water TAG guidelines [4] (see Figure A1) in the Appendix A.2. Considering these historical developments, this review was conducted for two periods, "1993–2017" and "2018–2024", marking the year 2018 as a pivotal year by publication of the FAO LEAP water TAG guidelines [4], Drastig et al. [5], and other key publications of ISO 14046 standard in 2016 (close to 2018) and the recommendations of the WULCA working group to the Life Cycle Initiative in 2017–2018 [12].

The review period was divided into two sections, as an earlier, extensive literature review from "1993–2017" [5] was used and supplemented with a literature review from recent years, "2018–2024". Four combinations of keywords, "water productivity, water use efficiency, water footprint, plus livestock" and "life cycle assessment, plus water use and livestock" were used to search published literature in the two periods: "Period 1993–2017", using Google Scholar and Web of Science [5,20], and "Period 2018–2024", using Web of Science (Figure 1).

A full list of references used in the review can be found online at https://doi.org/10.5281/zenodo.15743700.

For the "Period 1993–2017", the articles from the "Google Scholar" were selected if the search keywords appeared in the title only, as it was impossible to choose the keywords appearing in the keywords list or the abstract. However, the literature results with the search keywords appearing anywhere in the text were too many, with the keywords mostly only appearing in the general text descriptions, and thus not relevant for the focused literature review. The review studies collection, consisting of peer-reviewed publications, conference publications, and gray literature, was supplemented with relevant publications from the International Center for Tropical Agriculture (CIAT), the National Institute of

Agricultural Technology (INTA), and Agribenchmark, which had published various studies on livestock water use. A total of 52 articles were selected for the review of studies for the "Period 1993–2017", based on publications presenting an analysis of accounting water productivity of livestock supply [5]. In this publication [5], a review of the objectives, scales, and approaches of 52 studies (before 2018) was conducted.

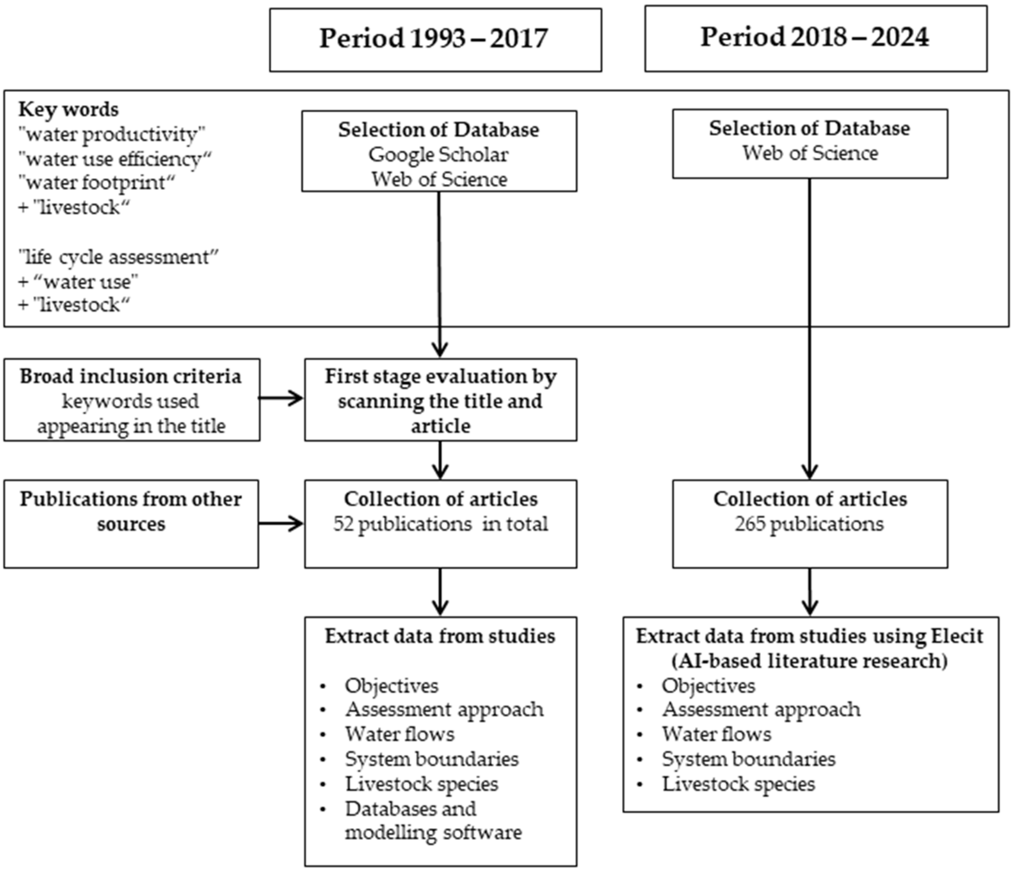

Figure 1. Outline of keywords, databases, tools, and criteria used for the collection of existing studies for review on water use in livestock production systems and supply chains for the two review periods: "1993–2017" and "2018–2024".

For the "Period 2018–2024", the same literature search keywords (Figure 1) were used to find literature using the database "Web of Science". The keywords were searched for in the title, abstract, and keywords. Only indexed peer-reviewed publications were used. A total of 265 studies were enlisted for the review (Figure 1). The full list of references used in the review is provided in the public database Zenodo (see Supplementary Materials). The latter period yielded too many articles, so we decided to use an AI-based program to extract information from the 265 articles listed in Web of Science. For the extraction of information and analyses of the literature, Elicit (https://elicit.com/), an AI-based literature research tool, was used (see Appendix A.3: Information and advice regarding Elicit). Here, the extraction of information was performed using the function "Extract data from papers" from the 265 articles selected for the review from "Period 2018–2024". Columns were created using the questions in Appendix A.4 "Columns Elicit". The chosen "Answer Structure" was "yes/no/maybe". The use of Elicit helped to extract and summarize key information from the selected articles. However, it is worth noting that this could potentially result in the extraction of unclear key review data from some studies, due to either a lack of poor descriptions in some articles and/or potential inaccuracy by the applied large language model (LLM) itself [21], creating some level of uncertainty in the relevant review data extracted from the selected articles. The results of the AI research were examined manually on a random sample basis. However, in this study, any unclear review data extractions were assigned as "unclear/other" in the results and discussion of the literature review conducted.

A review database was created for the two review periods, "Period 1993–2017" and "Period 2018–2024" (Figure 1). The criteria used to review the collated studies were as follows: (1) type (species) of livestock production system analyzed; (2) objectives of the study; and (3) assessment approach, water flows, and system boundaries used. For the review of the "Period 1993–2017", the articles were further analyzed in terms of the databases and modeling software used.

2.3. Key Review Findings

2.3.1. Livestock Production Systems

The review highlights that the beef and dairy milk production systems had been analyzed in more than 80% of the selected studies (317 in total) reviewed in both review periods (See Figure 2 and Table 1). The other types of livestock, such as sheep, poultry, and swine production systems, were also the focus of 86 or more studies each. A high number of others/unclear results were identified, potentially due to other types of livestock and unclear descriptions found by the human assessment for the review "Period 1993–2017" or due to unclear descriptions found by the AI tool, Elicit [21], used for the review "Period 2018–2024". However, this high number of others/unclear results made it difficult to provide more accurate information on the livestock types studied from the analysis of the publications.

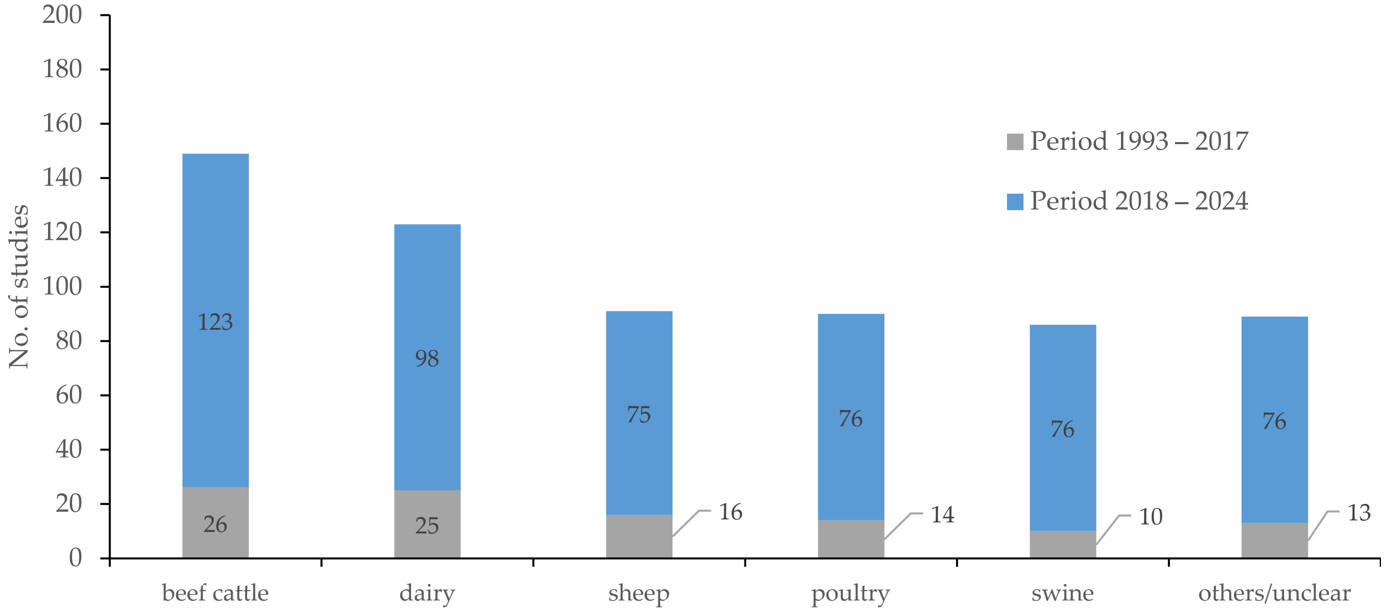

Figure 2. Livestock species included in the reviewed articles, including 52 publications of the "Period 1993–2017" and 265 publications of the "Period 2018–2024".

Table 1. Percentage share of different livestock species in the reviewed articles, including 52 publications of the "Period 1993–2017" and 265 publications of the "Period 2018–2024". Some studies included multiple species, allowing for several entries per article.

Time Period	Others/Unclear	Swine	Poultry	Sheep	Dairy	Beef Cattle
Period 1993–2017	25%	19%	27%	31%	48%	50%
Period 2018–2024	29%	29%	29%	28%	37%	46%

2.3.2. Study Objectives

Figure 3 reveals a significant shift in research priorities within livestock water use assessment studies over the past three decades, comparing two distinct periods: 1993–2017 and 2018–2024. During the earlier "Period 1993–2017", the research landscape was characterized by a predominance of studies with "other objectives/unclear" (58%), as per human assessment. The human assessment revealed that the differences stemmed from methodological approaches rather than classification challenges. The reviewed studies focused on livestock water use impact assessments comprised only 25% of the publications, while livestock water efficiency assessments represented 17% of the publications. Notably, no studies addressed both objectives of livestock water efficiency and impact simultaneously during the 1993–2017 period (Figure 3). In the more recent "Period 2018–2024", the share of the reviewed studies with "other objectives/unclear" classification increased substantially to 68% and remained the largest category. This could be potentially due to unclear descriptions in some articles and/or potentially inaccurate classifications by the AI tool, Elicit [21], used for the review "Period 2018–2024". However, it corresponds to a relatively large share of the reviewed studies classified as "other objectives/unclear" (58%) by the human assessment for the earlier "Period 1993–2017".

While the "other objectives/unclear" category remained dominant across both periods, there was a notable shift from water impact assessment focus (25% to 9%) and water efficiency focus (17% to 15%), suggesting either a diversification of research approaches or challenges in the studies' classification. The LCA studies focused on the assessment of impacts of water consumption were more numerous after 2018, rising from 13 studies to 25 studies. However, a large percentage of studies in the "Period 2018–2024" were identified as others/unclear, potentially due to unclear descriptions, the inaccuracy of the AI-based tool [21], and/or the questions asked, as follows:

- Was the main objective of the study to evaluate the environmental impacts of water consumption?
- Was the main objective of the study the improvement of water efficiency? (see Appendix A.4: Columns Elicit, Objectives).

However, most significantly, 8% of the studies were assessed as incorporating both water efficiency and impact assessment objectives, marking the emergence of integrated approaches since 2018 onwards, which were missing in the earlier "Period 1993–2017". This aligns well with the FAO LEAP water TAG guidelines [4] that explicitly recommend calculating both water use efficiency (also known as water productivity) and water impact indicators. In the review "Period 2018–2024", about 20 studies [10,22–40] mentioned the necessity to calculate both water efficiency and water impact indicators, as recommended by the FAO LEAP water TAG guidelines [4,10]. However, in the review "Period 1993–2017", no study was classified as mentioning these two objectives together (Figure 3).

The review assessment in Figure 3 indicates that the livestock water use assessment is gradually moving toward more integrated approaches that consider both water productivity and environmental impact dimensions together.

2.3.3. Assessment Approaches

The reviewed studies showed differences in their assessment approaches regarding the relationship between inputs and outputs for the quantification of water use metrics. In livestock production systems, water productivity is generally applied to measure the value or benefit (product or services) derived per unit of water used. The denominator is the unit of water consumed (e.g., produce biomass per liter or m^3 of water consumed) [15,16]. However, various studies differed in their account for different flows of water use, e.g., calculating the ratio of biomass/transpiration; biomass/evapotranspiration;

or biomass/water input, to quantify WP values. Similarly, inconsistencies exist in assessment of environmental impacts of water use in livestock production systems.

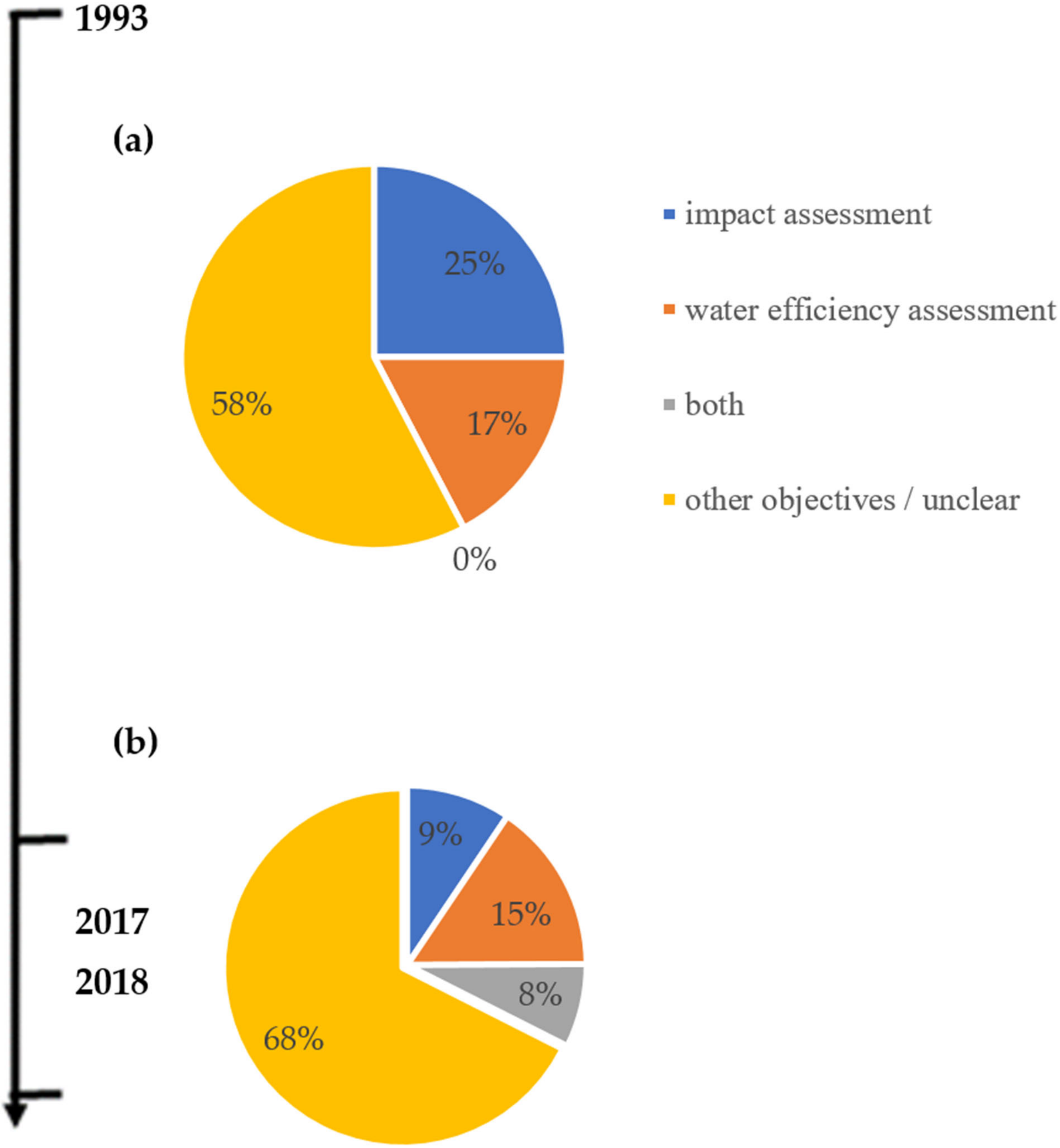

Figure 3. Percentage share of the main objectives of the reviewed studies: (**a**) 52 publications of the "Period 1993–2017" and (**b**) 265 publications of the "Period 2018–2024".

The reviewed publications were classified according to their use of water input and water output formula, i.e., "water input over farm output (WF)" or "farm output over water input (WP)" (Figure 4). Comparing the review "Period 1993–2017" with the review "Period 2018–2024", it appeared that the WF method had been used less in the recent years (Figure 4). Interestingly, the use of both WF and WP had increased in recent years, from none during the review "Period 1993–2017" to about 9% of the studies during the review "Period 2018–2024" (Figure 4). However, a high number of unclear results in the review "Period 2018–2024", based on the AI review tool [21,41], made the interpretation difficult conclusively.

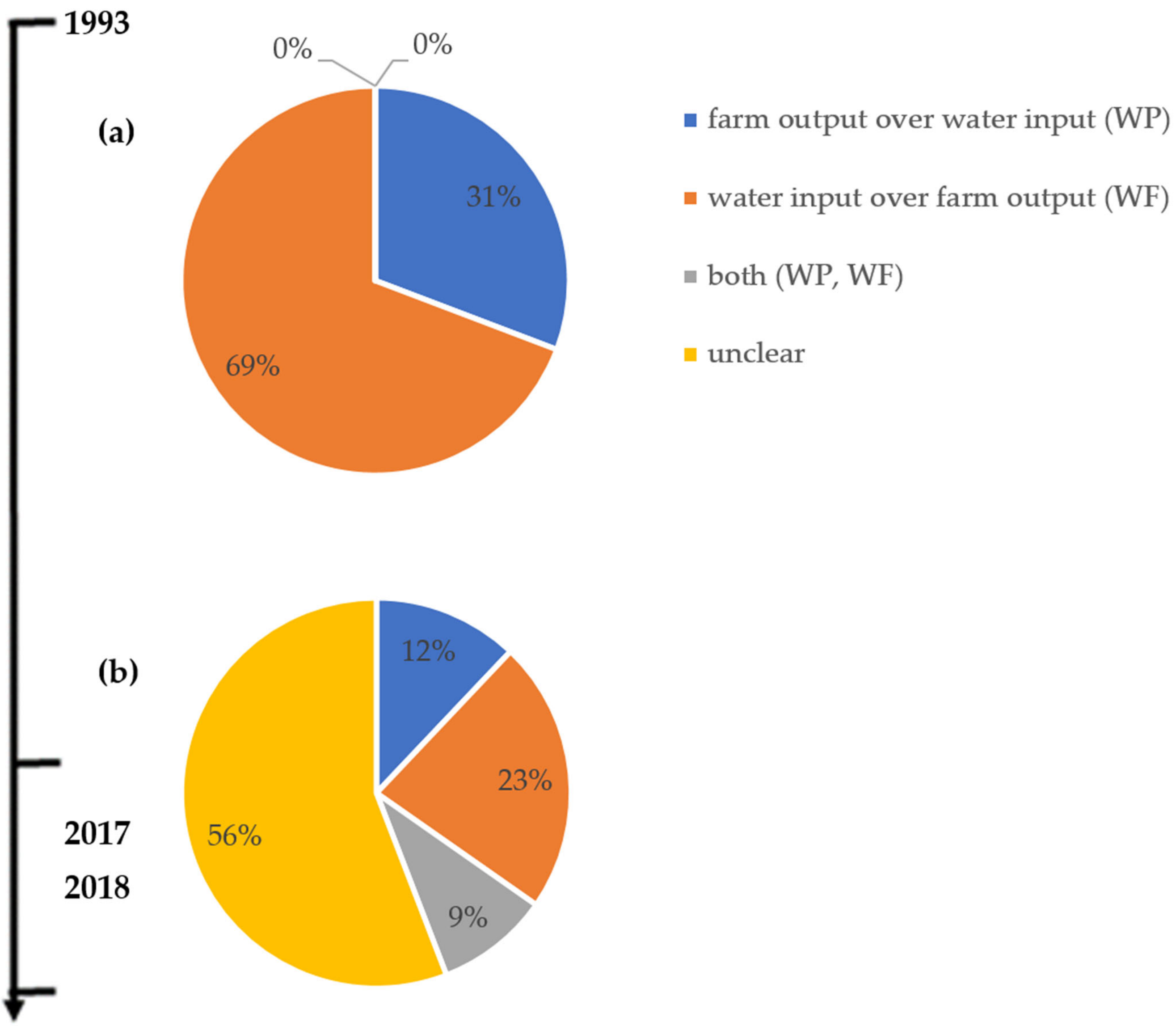

Figure 4. An overview of different water use assessment approaches of the reviewed studies: (**a**) 52 publications of the "Period 1993–2017" and (**b**) 265 publications of the "Period 2018–2024". WP: water productivity; WF: water footprint.

Figure 4 clearly highlights a lack of applying a comparable water-related metric. This could be attributed to different objectives of the studies reviewed; however, the use of different definitions of water use metrics makes it difficult to compare the potential water productivity of different livestock production systems in different studies. Out of the 15 LCA-based studies from the review "Period 1993–2017", ten (10) studies quantified a blue water scarcity indicator (e.g., water stress index based on [42] or included 3–4 stages of LCA to measure the contribution of water consumption to water scarcity [43,44]. However, five studies conducted only a water footprint inventory (LCI: life cycle inventory) analysis and no assessment of the water impacts of water consumption in livestock production systems [45]. Additionally, one investigation [46] evaluated changes in consumptive water use resulting from grassland-to-forest land-use transitions.

Most LCA-based studies from the review "Period 1993–2017" followed the ISO 14046 standard, summing up the water flow at each life cycle stage as part of life cycle impact assessment (LCIA) analysis. However, most LCA-based studies did not report the total water volumes used/consumed, but presented water impact equivalents, expressed in liters H_2O-e (e.g., [47–52]). Prior to 2016, the results of water impact assessments were often referred to as "stress-weighted water footprint/use" [42]. The FAO LEAP water TAG guidelines [4] give an extensive overview in chronological order of publication of blue water scarcity indicators. About 19% (ten) of LCA-based studies in the review "Period 1993–2017" used the water impact equivalents (H_2O-e) per unit produced, i.e., liter H_2O-e/kg, defined now as water scarcity footprint (ISO 14046:2014 [8]). In the review "Period 2018–2024", the share of studies reporting the water impact equivalents (H_2O-e) decreased to 13% of the reviewed studies. However, all of these articles used the WF accounting as per water input over farm output.

2.3.4. Accounting of Different Water Flows

The reviewed studies clearly differed in their accounting of different water flows in their assessment of livestock water use (Figure 5, Table 2). About 16 articles of the review "Period 1993–2017" did not account for evapotranspiration stemming from precipitation [53]. This included a number of LCA-based studies (e.g., [48,50,51,54]). Ridoutt et al. [47] argued that soil water consumption flows (i.e., green water) originating from precipitation may lack relevance for the assessment of water scarcity impacts of agriculture production systems.

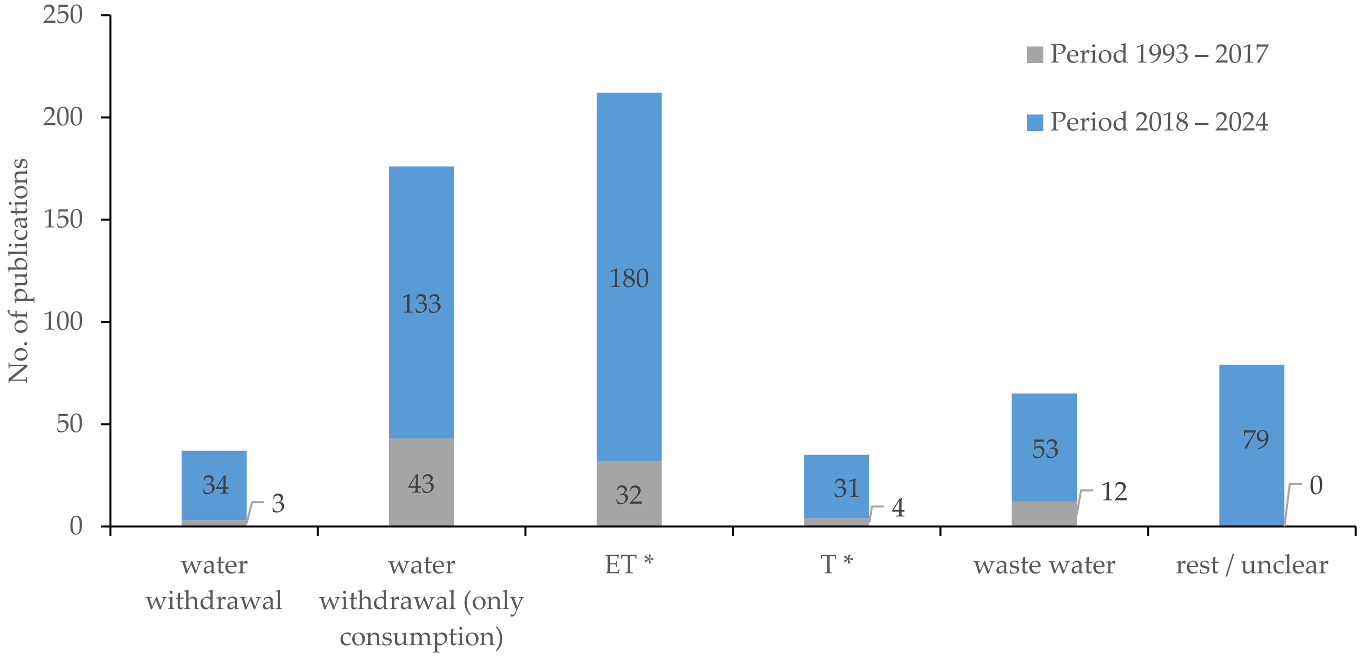

Figure 5. Number of studies accounting for different water flows out of 52 publications of the "Period 1993–2017" and 265 publications of the review "Period 2018–2024". ET: evapotranspiration; T: transpiration. * stemming from precipitation.

Table 2. Percentage share of studies accounting for different water flows out of 52 publications of the "Period 1993–2017" and 265 publications of the "Period 2018–2024". ET: evapotranspiration; T: transpiration.

Period	Rest/Unclear	Waste Water	Soil Water		Technical Water	
			T [1]	ET [1]	Water Withdrawal (Only Consumption)	Water Withdrawal
1993–2017	0%	23%	8%	62%	83%	6%
2018–2024	30%	20%	12%	68%	50%	13%

Note(s): [1] stemming from precipitation.

Considering soil water stemming from precipitation in the inclusion of evapotranspiration as soil water flow was accounted for in 62% of the publications of the review "Period 1993–2017" and in 68% of the publications of the review "Period 2018–2024" (Table 2). However, four articles (8%) of the review "Period 1993–2017" included only transpiration as a water flow from precipitation [17,55–57]. The inclusion of transpiration as water flow from precipitation was accounted for in only 12% of the publications of the review "Period 2018–2024".

Out of the 52 publications of the review "Period 1993–2017", only three articles accounted for water withdrawal, in which all water withdrawn for the farm's sake was considered as water input, not just evapotranspired irrigation water [17,55,56]. Similarly, only 34 articles out of 265 publications of the review "Period 2018–2024" accounted for water withdrawn as water input, including irrigation water and water in stables: drinking water, water for cleaning processes, and water for cooling processes. It seems plausible that the inclusion of water withdrawal was slightly more pronounced in recent years (Figure 5).

Regarding wastewater resp. water degradative use, a total of 12 articles (i.e., 23%) out of 52 publications of the review "Period 1993–2017", and 53 articles (i.e., 20%) out of 265 publications of the review "Period 2018–2024" included wastewater (Table 2).

2.3.5. System Boundary

A crucial consideration is whether to include only on-farm water consumption or to also account for water consumption in all interconnected stages of the entire livestock supply chain to capture the indirect water consumption of livestock products. The FAO LEAP water TAG guidelines [5] recommend the inclusion of different life cycle stages taking place before the livestock farm in the system boundaries.

However, about 58% of all reviewed publications between 1993 and 2024, including both review periods, used a cradle-to-farm gate boundary approach. In the review "Period 1993–2017", about 62% of 52 publications included indirect water use from feed production, but in the review "Period 2018–2024", only 18% of 265 publications accounted for indirect water use from purchased feed. However, a high number of unclear results (Figure 6) from the AI-based review tool [21,41] made this analysis and its interpretation difficult for both periods.

In the review "Period 1993–2017", about 27% of 52 publications included indirect water consumed from included water flows for meat and milk processing. However, in the review "Period 2018–2024", only 5% of 265 publications accounted for indirect water consumed from included water flows for meat and milk processing.

2.3.6. Databases and Modeling

The studies of the review "Period 1993–2017" employed diverse databases and models, encompassing both established and custom-developed frameworks (Table 3). Primary variables included farm operations data, plant physiological parameters, water withdrawal records, climatic variables, soil characteristics, and international trade statistics. However, life cycle assessment databases, particularly Ecoinvent, were used by a number of studies [58].

Furthermore, the review analysis identified a total of 23 unique data sources used across the reviewed studies from 1993 to 2017. However, primary farm data collection was the most prevalent data source, utilized in 18 studies, followed by unspecified precipitation/climate data in 14 studies. German Weather Service (DWD) meteorological data, soil texture data, and AQUASTAT were each employed in five (5) studies. A number of studies used 14 unique models and/or software applications to quantify different water flows, including evapotranspiration or transpiration, feed consumption patterns, and livestock drinking water requirements. CropWat was the most frequently used model, appearing in four (4) studies, while AgroHyd Farmmodel and SimaPro were each utilized in two (2) studies. The majority of other data sources and models were used only once, indicating considerable diversity in the use of data sources, including databases and models, for the assessment of livestock water use during the review "Period 1993–2017" (Table 3).

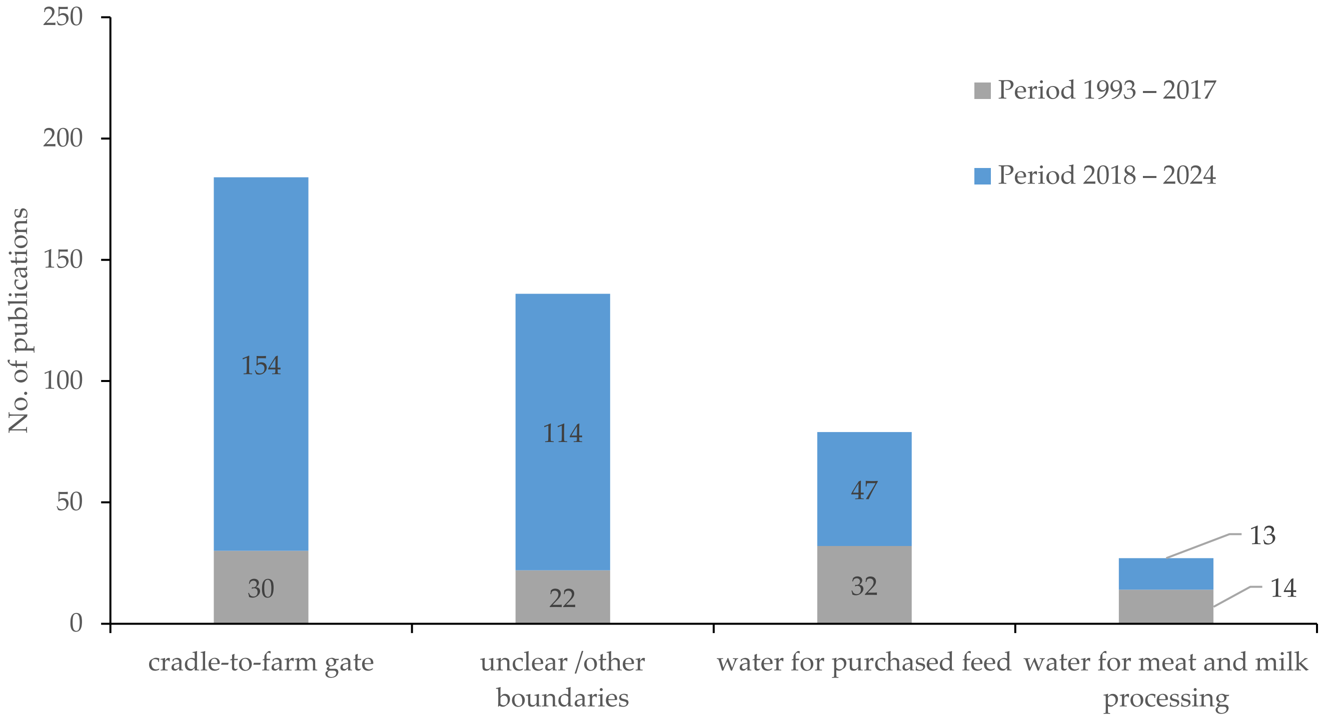

Figure 6. Analysis of system boundaries of 52 publications of the "Period 1993–2017" and 265 publications of the "Period 2018–2024".

Table 3. List of different (a) data sources and (b) models/software used in livestock water use studies of the period 1993–2017.

(a) Data Type	Source	Studies	References
Farm-level data	Primary farm data collection	18	-
Climate and Weather	Precipitation/climate data (unspecified source)	14	-
	German Weather Service (DWD)/local meteorological data	5	[59]
	Climwat	2	[59]
	AGRITEMPO	1	[60]
Soil and Land	Harmonized World Soil Database version/oil texture data	5	[61]
	FAO global agro-ecological database	1	[62]
	Leaf area index	1	[63,64]

Table 3. *Cont.*

(a) Data Type	Source	Studies	References
Water Resources	AQUASTAT	5	[65]
Agricultural Statistics	ABARES (Australian Bureau of Agricultural and Resource Economics)	4	[66]
	International Farm Comparison Network (IFCN)	2	[67,68]
	Agricultural Census data	1	[69]
	German Livestock Breeding Report 2008	1	[70]
	Association for Technology and Structures in Agriculture (Germany)	1	[71,72]
	South African Milk Processors' Organization (SAMPRO)	1	[73]
	FAO gridded livestock of the world	1	[74]
	Nationwide statistics (unspecified)	1	-
Economy and Trade	World Bank online database	1	[75]
	Trade data from PC-TAS	1	[76]
	Environmental input-output data	1	[77]
LCA Databases	Ecoinvent database	2	[58]
	FAO gridded livestock of the world	1	[74]
	Nationwide statistics (unspecified)	1	-
(b) Application Type	**Model/Software**	**Studies**	**References**
Water Management	CropWat 8.0	4	[78]
	AgroHyd Farmmodel	2	[79,80]
	New_LocClim software 1.06	1	[81]
LCA Software	SimaPro 9.0	2	[82]
	Australian hybrid LCA model	1	[83]
Crop/Pasture Modeling	Lund-Potsdam-Jena managed Land (LPJmL) model	1	[84]
	GRASP	1	[85]
	MEDLI 1.0	1	[86]
Farm System Modeling	BUDGET 6.0	1	[87]
	MOTIFS	1	[88]
	TIPI-CAL-5.2 model	1	[89]
Data Management	Database and spreadsheet model	1	[90]
Classification Systems	Global livestock production system classification scheme	1	[91]

However, the use of different secondary databases and models could be a source of uncertainty in assessment of water use in livestock production systems [4]. In their review article, Drastig et al. [92] proposed a tiered approach to qualifying uncertainties and also discussed the scarcity of available high-quality input data, which impacts the reliability of nutritional water productivity analysis outputs.

3. Review Discussion

3.1. Lack of Consistency in the Methodological Approaches

The above-described literature review results clearly highlight a lack of consistency in methodological approaches for the assessment of livestock water use. The reviewed studies were different in their inclusion or exclusion of background processes (systems boundaries), accounting of different water flows, and consideration of precipitation-derived water consumption (green water). Another critical issue pertains to the application of varied secondary data sources and models, alongside the general absence of uncertainty evaluation, which encompasses input data, model, and analytical choice uncertainties.

However, the historical development of livestock water use assessment methods is a remarkable evolution from different distinct methodological origins towards a unified approach. Figure A1 shows the most important historical events in the field of "assessment of water use in livestock", including the origins, the convergence, and the current frameworks of water use also relevant to livestock water use. The evolution of water use assessment methods represents a convergence of three originally distinct approaches: water productivity, life cycle assessment (LCA), and water footprint assessments (Figure A1). Though all three approaches emerged in the 1960s, they developed with different purposes and methodologies.

Water productivity was developed primarily to improve water efficiency in agricultural production systems. Viets (1962) defined water use efficiency as the carbon assimilated and crop yield per unit of (evapo)transpiration [93]. Molden (1997) [14] later formalized the framework of water productivity as a measure of output per unit of water used. The livestock water productivity (LWP) method, developed by Peden et al. (2007) [94], measures the ratio of beneficial livestock products and services to water depleted in their production. The AgroHyd group at the Leibniz Institute for Agricultural Engineering and Bioeconomy developed innovative water productivity assessment methods, combining hydrological and agronomical approaches to adapt agricultural production to global changes, including different frameworks (e.g., "Water use indicators at farm scale" [17]). Prochnow et al. 2012 [17] deviated by accounting for water withdrawn and transpiration as water inputs for farming, instead of evapotranspiration being accounted for by commonly used methods [14,93,94]. Based on these frameworks, the web-based AgroHyd Farmmodel [79,80] was developed to identify hydrological processes, model water flows, and calculate water-based indicators for different farm systems used for plant and livestock production. The model highlighted significant variations in simulated water productivity between and within crops and livestock production in the study regions.

However, LCA focused on the environmental impacts of industrial products, while footprint assessments aimed to quantify natural resource consumption at societal scales. These approaches developed independently through the 1970s–1990s, creating separate scientific communities with minimal interaction (Figure A1).

The late 2000s marked a turning point when researchers and practitioners recognized the complementary nature of these approaches. This led to LCA-based water footprint methods that bridged previously separate fields. The integration culminated in 2014 with ISO 14046, which unified water footprint assessment within LCA standards [8]. Later, ISO 14046:2016 mandated parallel calculation of water productivity and environmental impact assessment approaches through a comprehensive LCA framework. This standard requires a thorough assessment of water-related environmental impacts before applying the term "water footprint", ensuring scientific rigor and consistency. The most important "historical events" are marked by this publication in 2016 and by the recommendations of the WULCA-group to the Life Cycle Initiative in 2017–2018 [12].

As the current framework and goals, the UN Sustainable Development Goals (2015) established Target 6.4 to substantially increase water use efficiency across all sectors by 2030 [95]. Progress is tracked through SDG indicators 6.4.1 (water use efficiency, [96]) and 6.4.2 (water stress levels, [97]), first reported in 2018. The FAO LEAP water TAG guidelines [4,10] advocate for an integrated approach combining the assessment of both water productivity and water scarcity footprint analysis. This dual-metric framework recommends that the metric for water productivity should take into account both direct and indirect water consumption, supplemented by water scarcity footprint analysis for environmental impact assessment. This approach enables informed decision-making that balances operational efficiency with environmental sustainability.

The historical developments (Figure A1) support the review finding of the pre- vs. post-2018 results (Figures 3 and 4). The water impact assessment method, as a study objective, received a stronger focus in recent publications, in the review "Period 2018–2024" (Figure 4). This coincides with the publication of the ISO 14046 standard in 2016 and also the recommendations of the WULCA working group to the Life Cycle Initiative in 2017–2018 [12]. This explains why the LCA studies focused on the impact of water consumption were more numerous after 2018, since the recommendation is what allowed for this work to take place. However, in the review "Period 2018–2024", only 8% of 265 publications mentioned the necessity to calculate both water efficiency and water impact indicators as recommended by the FAO LEAP water TAG guidelines [4,10]. In the earlier review "Period 1993–2017", no publication mentioned these two objectives together in their assessment. While the proportion of the integrated studies remains relatively small at 8%, the emergence of research incorporating both water efficiency and water impact assessment methodologies indicates that standardization initiatives, particularly the FAO LEAP water TAG guidelines [4,10], are gradually shaping research practices toward more holistic evaluation frameworks. As recommended by Berger et al. [9], future research could be tackled jointly by the different communities.

The review also highlights differences in accounting for different water flows in the assessment of water use for livestock production systems. Only a few studies (38 out of 317) accounted for all water withdrawal over the entire review period from 1993 to 2024. Accounting for water withdrawal has been slightly more pronounced in recent years, from 2018 to 2024. However, water withdrawal remains largely unaccounted for in the reviewed livestock water use studies. This is an important aspect, as water withdrawals could potentially create local site-specific water impacts. Also, a few studies accounted for transpiration only as water consumption. From a hydrological perspective, evaporation and transpiration are both water flows (as water consumption) and must be targeted to optimize by water management practices in livestock production systems.

The reviewed studies also differed in their definition of system boundaries applied for the assessment of livestock water use. The FAO LEAP water TAG guidelines [4,10] recommend the assessment of "both direct and indirect water consumption, since indirect consumption (in some livestock production) may be much greater than the direct water consumption". However, the review highlights an inconsistency in the accounting of direct and indirect water flows in the study analysis. Accounting for both direct and indirect water flows is highly important. For example, a large share of water use in livestock production is associated with feed consumption [98], and only 62% of 52 publications accounted for indirect water use embedded in feed production in the earlier time period from 1993 to 2017. Similarly, indirect water use could be significant in the processing of livestock products, as demonstrated by accounting for the indirect water use embedded in electricity use in dairy processing in Punjab (India) [11]. Clearly, inconsistency in the accounting of direct and indirect water flows amounts to an incomparable assessment of water use in different livestock production systems across diverse climate and geographical locations.

It is evident from this comprehensive review of relevant publications from the two periods, the "Period 1993–2017 [4,5], and the "Period 2018–2024" presented above, that the methods and approaches used to assess livestock water use remain inconsistent. This lack of consistency makes it difficult to compare various studies' results to identify opportunities for improving water productivity and reducing the water scarcity impacts of livestock production systems. However, the AI-based review tool [21] also identified a high number of others/unclear results in terms of their descriptions of the agricultural systems themselves and the water use assessment methods used in the analysis of the publications. This could be potentially due to a lack of clearly defined and described methods and approaches, which made it potentially difficult to extract key review information by the AI-based review assistant tool [21]. However, a lack of proper study methods, definitions, and descriptions is key to advancing and harmonizing water use assessment in livestock production systems and supply chains.

3.2. Significant Contributions from the Review: The Assessment of Productivity and Environmental Impact Indicators in Oarallel, and the Importance of Inclusion of "All Water Withdrawal"

The reviewed studies had various study objectives, ranging from quantification of water flows to raising awareness. As per the recommendations of the FAO LEAP water TAG guidelines [4], "only the overall water productivity metric of a production system shall be accompanied by the water scarcity footprint of the analyzed system not the other way round". However, the water scarcity footprint can be used on its own. This can be explained by the different objectives of the productivity perspective and the environmental perspective. According to the definition by the LCA community, a water footprint metric quantifies the potential environmental impacts, providing an environmental perspective without considering the water productivity. Water footprint indicators from different locations with different livestock systems and supply chains can be compared. A water productivity metric enables the assessment of agricultural farming measures to improve the efficiency of agricultural water use. This provides a productivity perspective. However, water productivity indicators from different locations, livestock systems, etc., cannot be compared without additional information on the environmental impacts associated with the production systems analyzed. To understand this challenge, it is helpful to consider the often-cited figure of 15,000 L of water required to produce 1 kg of beef, which can have very different environmental impacts depending on location. In this case, only the combined indicators from a water productivity and environmental perspective offer a robust understanding of the pressure that the livestock production systems and supply chains exert on local water resources.

However, most of the reviewed studies accounted for consumptive water flows in their assessment of livestock water use. According to Döll et al. [98], water withdrawals can be up to three times as high as water consumption locally, and surface water withdrawals could be potentially associated with environmental impacts on local waterways. For this reason, as per the recommendations of LCA methods [99], e.g., in [100], water withdrawals should be analyzed at each interconnected stage of livestock production systems and supply chains. The accounting of water withdrawals would align livestock water use assessments to water use indicators, such as the level of water stress (SDG 6.4.2 indicator) defined to measure progress towards achieving the sustainable development goals (SDGs), which relates freshwater withdrawal to available resources [100].

4. Conclusions and Recommendations

4.1. Practical Implications for Researchers, Practitioners, and Policymakers

This review suggests that a robust and consistent assessment of water use in livestock production systems and supply chains remain a challenge. The reviewed studies differ in terms of their accounting of different water flows, setting the system boundaries, and quantification of water productivity and impact metrics.

To advance and harmonize the assessment of livestock water use, the following are suggested.

4.1.1. Diversification of Livestock Production System Studies

Objective: To achieve comprehensive coverage of all livestock production systems in water use assessment research.

Current Gap: The majority of reviewed studies from 1993 to 2024 have predominantly focused on beef cattle and dairy farms, with relatively limited research on sheep, poultry, and swine production systems.

Recommendation: Conduct additional case studies following FAO LEAP water TAG guidelines [4,10] for all types of livestock production systems under comparable production conditions, including agricultural factors (climate, soil, and farming practices), animal-related factors (genetics, nutritional management, barn types), and other locally relevant factors to improve overall water use productivity. With diverse case studies, we expect to gain in-depth knowledge and information for further development and application of a consistent methodological framework to diverse real-world livestock production systems. It is expected to facilitate a valid comparative assessment of potential water productivity and environmental impacts of livestock production systems at different scales and locations. Comprehensive assessment across all livestock sectors is essential for developing universally applicable water use assessment frameworks and understanding sector-specific water use patterns.

4.1.2. Integrated Assessment of Water Productivity and Water Scarcity Impact

Objective: To promote holistic assessment of water use that addresses both water efficiency and environmental impact dimensions.

Current Gap: Limited studies assess both water scarcity footprint and water productivity simultaneously, offering somewhat limited assessment of water use in diverse livestock production systems and supply chains across different regions.

Recommendation: Further develop and implement a comprehensive and consistent assessment of both “water scarcity footprint” and “water productivity” [4,10], accounting for both direct and indirect water flows in livestock production systems and supply chains. An integrated assessment of water scarcity footprint and water productivity analysis could help identify hot-spots for simultaneous improvements in livestock water productivity and reduce its environmental impacts.

4.1.3. Comprehensive Water Flow Accounting

Objective: To ensure complete and accurate accounting of all water flows in livestock production systems.

Current Gap: Many studies focus only on consumed water fractions rather than total water withdrawals, potentially underestimating local water resource impacts.

Recommendation: Include all water withdrawals, not only consumed fractions, in assessment frameworks. Analyze highly localized water withdrawals at each stage of the livestock production chain and contextualize them within local water budgets, recognizing that water withdrawals can be up to three times higher than water consumption locally. A comprehensive water flow accounting process is critical for understanding true local water resource impacts and developing appropriate management strategies.

4.1.4. Enhanced Assessment of Precipitation-Derived Water Consumption Flows

Objective: To improve the understanding and management of precipitation-derived water use in livestock production systems.

Current Gap: Insufficient attention to precipitation-derived soil water use despite its dominance (4–5 times greater than withdrawal water) in global crop production for feedstuff in livestock [101].

Recommendation: Include a comprehensive assessment of precipitation-derived water consumption in livestock water use assessments [102]. Precipitation plays a key role in feed production for livestock production systems. Therefore, further develop and implement a hydrology-based approach for calculating precipitation-derived soil water inputs (green water) to feed production for livestock systems [103] and focus specifically on the transpiration fraction that contributes to plant biomass production. An enhanced assessment of precipitation-derived soil water use is essential for improving water productivity in predominantly rainfed livestock production systems and bridging the traditional division between rainfed and irrigated agriculture approaches [104].

4.1.5. Expansion of System Boundaries

Objective: To capture comprehensive direct and indirect water consumption across the entire livestock production chain.

Current Gap: Limited inclusion of upstream and downstream processes in water use assessments, leading to incomplete impact evaluation.

Recommendation: Expand system boundaries to include different life cycle stages occurring before and at the livestock farm, capturing both direct and indirect water consumption. Account for major inputs, such as electricity and its associated indirect water consumption, in livestock product production and processing [11]. Well-defined system boundaries, including different life cycle stages occurring before and at the livestock farm, are necessary for a comprehensive assessment and identification of opportunities for optimization of water use across the entire livestock production and supply chain.

4.1.6. Improvement of Data Quality and Uncertainty Management

Objective: To enhance the reliability and accuracy of water use assessments through improved data sources and uncertainty analysis.

Current Gap: Inconsistent data quality and limited uncertainty analysis in existing studies, affecting the reliability of findings.

Recommendation: Prioritize primary farm data and locally calibrated and validated models and databases. Incorporate catchment-scale water flows and environmental flow requirements in localized water scarcity footprint quantification [105]. Conduct robust uncertainty analysis for secondary data sources as per FAO LEAP water TAG guidelines [4,10]. High-quality, locally relevant data combined with comprehensive uncertainty analysis is fundamental for developing reliable and actionable water use assessment results that can inform effective policy and management decisions.

4.1.7. Development of Farm-Scale Water Management Tools

Objective: To provide practical tools for on-farm water use optimization and decision-making.

Current Gap: Limited availability of accessible tools for farmers to understand and optimize their water use patterns.

Recommendation: Develop and implement locally calibrated and validated tools to quantify and assess water use matrices (water productivity and water scarcity footprint) based on different water flows [17]. This is expected to assist farmers and water managers in better understanding different water flows and utilization on their farms, enabling optimization through adapted agronomic measures and improved farm management practices. On-farm water use tools must include method development for the evaluation of the best management practices to help optimize the water use of livestock farms. Farm-scale tools are crucial for translating research findings into practical, actionable water management improvements at the production level.

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Appendix A

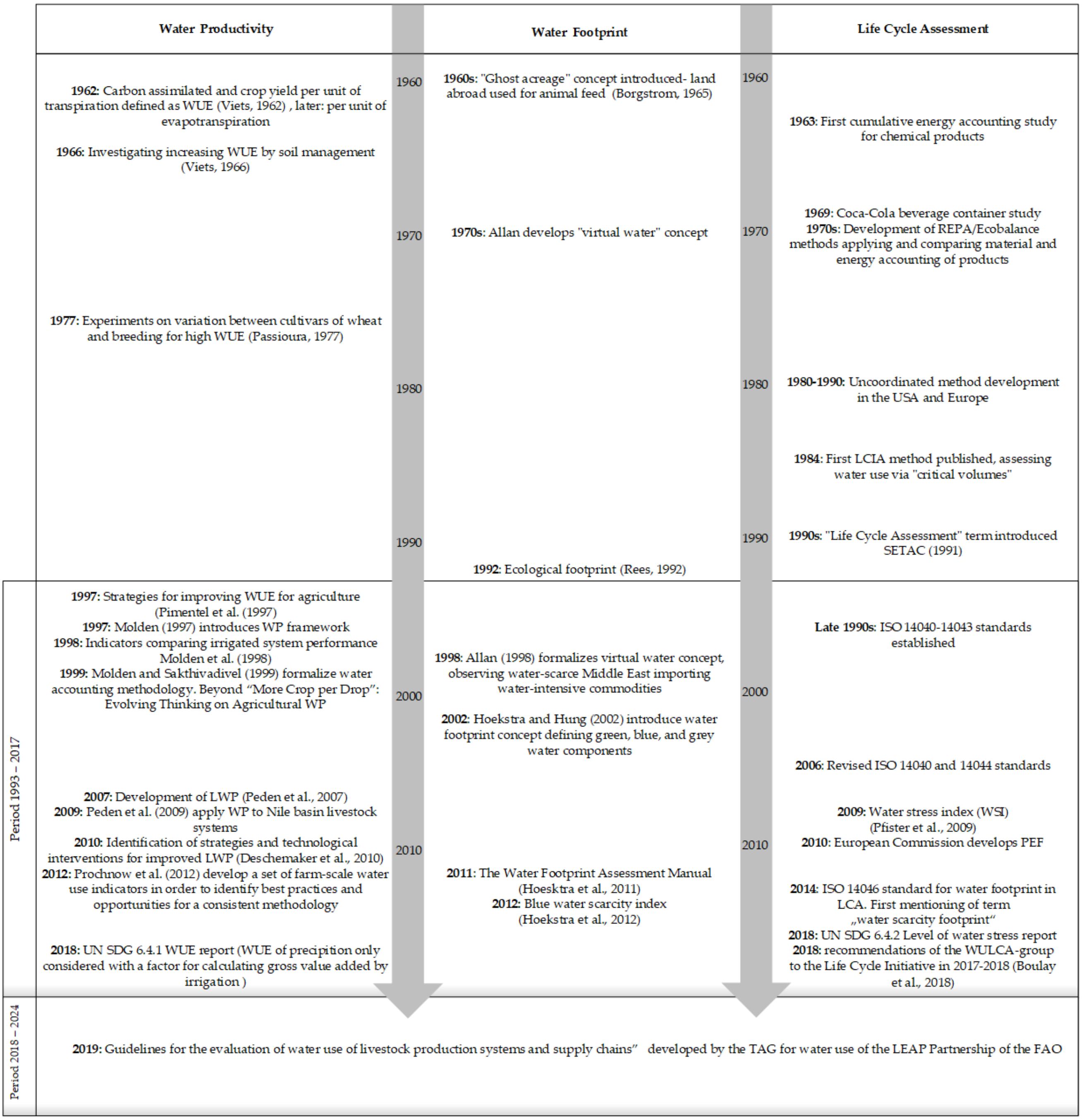
Appendix A.1. Glossary of Hydrological Terminology

Table A1. Glossary of Hydrological Terminology.

Blue Water	Encompasses freshwater flows derived from surface runoff or subsurface percolation that contribute to freshwater bodies, including lakes, reservoirs, rivers, and aquifers. Soil moisture is classified as blue water when it originates from irrigation applications, results from hydrological phenomena such as flooding, or derives from spring discharge or capillary rise processes
Direct Water	Direct water consumption is defined as water utilization within the immediate control or boundaries of the system under investigation. In farm-level studies, for example, on-farm water consumption represents direct consumption. Direct water consumption (foreground) encompasses water use that falls under the direct control or management of the study's focal system. For instance, in a farm-level study, direct water accounts for all on-farm water consumption.
Green Water	Precipitation water that is stored as soil moisture and eventually transpired or evaporated
Indirect Water	Indirect water consumption is outside the control of the focus of a study (e.g., water consumption in the supply chain of inputs). Indirect water accounts for water use occurring outside (background) of the study's focal system, such as water consumed throughout the supply chains of purchased inputs, materials, and services
Technical Water	Technical water is made up of tap water and irrigation water, which can be withdrawn from surface or groundwater. It includes water for intake (drinking), cleaning, cooling, and irrigation

Water Availability	The extent to which humans and ecosystems have sufficient water resources for their needs
Water Consumption	The term commonly refers to water removal from a drainage basin that is not returned to the same hydrological unit. Water consumption mechanisms include evaporation, transpiration, product integration, or release to alternative drainage basins or oceanic systems. Land-use change impacts on evaporation rates, exemplified by reservoir development, constitute water consumption
Water Footprint [9]	From the Water footprint assessment manual [7]: "an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer", which is "measured in terms of water volumes consumed (. . .) and/or polluted per unit of time". This footprint term can be further qualified to identify the type of water used (green, blue, gray) or to indicate the subject of the study (e.g., product, organization, nation) From ISO 14046 standard [8]: Water footprint: metric(s) that quantifies the potential environmental impacts related to water. If water-related potential environmental impacts have not been comprehensively assessed, then the term "water footprint" can only be applied with a qualifier. A qualifier is one or several additional words used in conjunction with the term "water footprint" to describe the impact category/categories studied in the water footprint assessment, e.g., "water scarcity footprint", "water eutrophication footprint", "non-comprehensive water footprint"
Water Productivity	The relationship between productive outputs and the water input for their generation, with benefits measured in various units, including mass, energy, or nutritional parameters per cubic meter of water
Water Scarcity	The extent to which water demand compares to the replenishment of water in an area, e.g., a drainage basin, without taking into account the water quality
Water Scarcity Footprint	A metric that quantifies the potential environmental impacts related to water scarcity (based on ISO 14046 [8]), specifically linked to water quantity. Water availability footprint refers to both water quantity and quality
Water Use	Water use encompasses all forms of water utilization by human activities, including but not limited to water withdrawal, discharge, and other anthropogenic activities within drainage basins that affect water flows and quality. This definition incorporates in-stream uses such as fishing, recreation, and transportation
Water Withdrawal	Water withdrawal constitutes the anthropogenic extraction of water from water bodies or drainage basins, encompassing both permanent and temporary removal processes.
Water Withdrawal (only Consumption)	Proportion of water withdrawn that evaporates through evaporation and transpiration with respect to consumed withdrawn water

Appendix A.2. Historical Development of the Livestock Water Use Assessment Methods and Guidelines



Period	Year	Water Productivity	Water Footprint	Life Cycle Assessment
	1960	**1962:** Carbon assimilated and crop yield per unit of transpiration defined as WUE (Viets, 1962) , later: per unit of evapotranspiration **1966:** Investigating increasing WUE by soil management (Viets, 1966)	**1960s:** "Ghost acreage" concept introduced- land abroad used for animal feed (Borgstrom, 1965)	**1963:** First cumulative energy accounting study for chemical products
	1970	**1977:** Experiments on variation between cultivars of wheat and breeding for high WUE (Passioura, 1977)	**1970s:** Allan develops "virtual water" concept	**1969:** Coca-Cola beverage container study **1970s:** Development of REPA/Ecobalance methods applying and comparing material and energy accounting of products
	1980			**1980-1990:** Uncoordinated method development in the USA and Europe **1984:** First LCIA method published, assessing water use via "critical volumes"
	1990		**1992:** Ecological footprint (Rees, 1992)	**1990s:** "Life Cycle Assessment" term introduced SETAC (1991)
Period 1993 – 2017		**1997:** Strategies for improving WUE for agriculture (Pimentel et al. (1997) **1997:** Molden (1997) introduces WP framework **1998:** Indicators comparing irrigated system performance Molden et al. (1998) **1999:** Molden and Sakthivadivel (1999) formalize water accounting methodology. Beyond "More Crop per Drop": Evolving Thinking on Agricultural WP	**1998:** Allan (1998) formalizes virtual water concept, observing water-scarce Middle East importing water-intensive commodities	**Late 1990s:** ISO 14040-14043 standards established
	2000		**2002:** Hoekstra and Hung (2002) introduce water footprint concept defining green, blue, and grey water components	**2006:** Revised ISO 14040 and 14044 standards
	2010	**2007:** Development of LWP (Peden et al., 2007) **2009:** Peden et al. (2009) apply WP to Nile basin livestock systems **2010:** Identification of strategies and technological interventions for improved LWP (Deschemaker et al., 2010) **2012:** Prochnow et al. (2012) develop a set of farm-scale water use indicators in order to identify best practices and opportunities for a consistent methodology **2018:** UN SDG 6.4.1 WUE report (WUE of precipition only considered with a factor for calculating gross value added by irrigation)	**2011:** The Water Footprint Assessment Manual (Hoesktra et al., 2011) **2012:** Blue water scarcity index (Hoekstra et al., 2012)	**2009:** Water stress index (WSI) (Pfister et al., 2009) **2010:** European Commission develops PEF **2014:** ISO 14046 standard for water footprint in LCA. First mentioning of term „water scarcity footprint" **2018:** UN SDG 6.4.2 Level of water stress report **2018:** recommendations of the WULCA-group to the Life Cycle Initiative in 2017-2018 (Boulay et al., 2018)
Period 2018 – 2024		**2019:** Guidelines for the evaluation of water use of livestock production systems and supply chains" developed by the TAG for water use of the LEAP Partnership of the FAO		

Figure A1. Historical development of livestock water use assessment methods, following, e.g., Berger et al. [9] and Ran et al. [106], in relation to the two review periods "Period 1993–2017" and "Period 2018–2024". WUE: water use efficiency, WP: water productivity, LWP: livestock water productivity, REPA: resource and environmental profile analyses, LCIA: life cycle impact assessment, PEF: product environmental footprint, WULCA: water use in life cycle assessment. Literature included here: Viets (1962) [93], Viets (1966) [107], Passioura (1977) [108], Pimentel et al. (1997) [109], Molden (1997) [14], Molden et al. (1998) [16], Molden and Sakthivadivel (1999) [15], Peden et al. (2007) [94], Peden et al. (2009) [110], Deschemaker et al. (2010) [13], Prochnow et al. (2012) [17], Borgstrom (1965) [111], Rees (1992) [112], Allan (1998) [113], Hoekstra and Hung (2002) [114], Hoesktra et al. (2011) [7], Hoekstra et al. (2012) [115], SETAC (1991) [116]. Pfister et al. (2009) [42], Boulay et al. (2018) [12].

Appendix A.3. Information and Advice Regarding Elicit

Ought, a non-profit machine learning laboratory [21], developed the Elicit tool, which is commercially available as an online software. In this review article, the Elicit tool was applied to extract key information, using the function “Extract data from papers”, from the 265 uploaded articles found using Web of Science. The chosen “Answer Structure” was “yes/no/maybe”. Elicit applied a large language model (LLM) [21] to the uploaded PDFs. In the literature, regarding the potential of generative AI to extract qualitative data from PDFs using LLMs, an accuracy between 68.8% and 96.3% could be achieved (Table A2). However, challenges with missed data, hallucinations, and structural interpretation had to be faced, so human validation is always required.

Spillias et al. [117] demonstrated that AI-powered tools can enhance the evidence extraction phase of systematic reviews. Their comparative analysis revealed that Elicit, a purpose-built AI text-extraction platform, outperformed custom implementations using GPT-4 Turbo in terms of response quality. Additionally, Elicit exhibited better information retrieval, with reduced risk of overlooking pertinent data compared to the general-purpose language model approach. However, as per Whitfield and Hofmann [41], a researcher needs to verify the accuracy of the returned results. Elicit is considered an early-stage tool [21]. It is more helpful to think of Elicit-generated content as around 80–90% accurate, definitely not 100% accurate [118]. Elicit shares the same limitations as other LLMs, which is why a centaur model, human + machine, for the extraction of qualitative data from PDFs is still needed [41]. Although Elicit performs well in data extraction, it lacks the complex analysis processes required for understanding and synthesizing the literature.

Table A2. Estimates of the accuracy and reliability of large language models (LLMs), as a specific application of generative AI, for the extraction of information from the existing literature.

Tool Name	Accuracy Rate	Error Types	Human Validation Required
TrialMind [119]	72–83% across different topics	missed data and incorrect interpretation, particularly in extracting numerical results	Yes
Multiple AI models [120]	not mentioned	less effective at detecting ethical concerns and technical errors	Yes
Claude 2, GPT-4 [121]	Claude 2: 96.3%, GPT-4: 68.8%	errors mainly due to plugin issues for GPT-4	Yes
ChatGPT-4o [122]	92.40%	false data generation (5.2% of cases)	Yes
GPT, GPT-4 [123]	91%	lower sensitivity for including relevant papers	Yes
Claude 2 [124]	96.30%	missed data items (4 out of 6 errors)	Yes
Custom neural network [125]	74.01%	not mentioned	Yes
GPT-3.5, GPT-4 [126]	not mentioned	hallucinations, inability to detect tables/figures, incorrect interpretation of article structure	Yes

Furthermore, Elicit does not yet know how to evaluate whether one paper is more trustworthy than another, except by giving you some imperfect heuristics like citation count, journal, critiques from other researchers who cited the paper, and certain methodological details, e.g., sample size and study type. The AI tool summarizes the findings of a ‘bad’ study just like it summarizes the findings of a ‘good’ study [118].

As the authors of this review article noticed some incorrect results in articles they were familiar with, the accuracy of the Elicit tool was checked and validated for a limited number of samples. The following assessment was made: the AI tool Elicit can be used for an overview, but for larger datasets, such as in this publication, the results are subject to a certain degree of uncertainty. Like [41], the authors of the review article considered the potential benefits of using Elicit, such as the ability to customize search results into columns of detailed information. However, the output for Elicit's analysis depends on the input. Therefore, a high quality of data input was ensured or aimed for by using Web of Science for the selection of peer-reviewed publications [20]. Nevertheless, a high number of our results were returned as unclear/other, which may be due to the accuracy of the tool and/or potentially poor descriptions in some articles.

Further, the literature search analysis is recommended to identify the causes and potential solutions to any unclear/other outputs of key information extraction by the AI tool used.

The analysis conducted in this literature review, therefore, shows that the tool is more suitable for supporting the preliminary phases of systematic literature research than for advanced interpretation functions.

Appendix A.4. Columns Elicit Used in the AI-Based Review Tool

Appendix A.4.1. Objectives

- Was the main objective of the study to evaluate the environmental impacts of water consumption?
- Was the main objective of the study the improvement of the water efficiency?

Appendix A.4.2. Livestock

- Is milk production included in the study?
- Is beef cattle production included in the study?
- Is sheep production included in the study?
- Is poultry production included in the study?
- Is swine production included in the study?

Appendix A.4.3. Boundaries

- Is the study limited to the boundary from cradle-to-farm gate?
- Does the study include the water requirement for purchased feed?
- Does the study include the water requirement for meat and milk processing?

Appendix A.4.4. Water Flows

- Does the study cover all water withdrawals? Alternatively, the study could consider only the consumed portion of the withdrawal.
- Does the study take into account the evapotranspiration?
- Does the study only include transpired water?
- Does the study include wastewater?
- Does the study cover the blue water consumed?
- Does the study cover all the blue water withdrawn?
- Does the study take into account only the evapotranspiration stemming from blue water?

Appendix A.4.5. Indicators

- In the study, is the agricultural yield divided by the water consumption (i.e., kg/m^3) and calculated as an indicator?

- Is water consumption divided by agricultural yield in the study (i.e., m^3/kg) and calculated as an indicator?
- Are the final results of the study expressed and compared in water equivalents (H_2O-e) per unit produced, i.e., liters H_2O-e/kg?

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