Daylighting and electric lighting for sustainable cattle buildings

A systematic literature review

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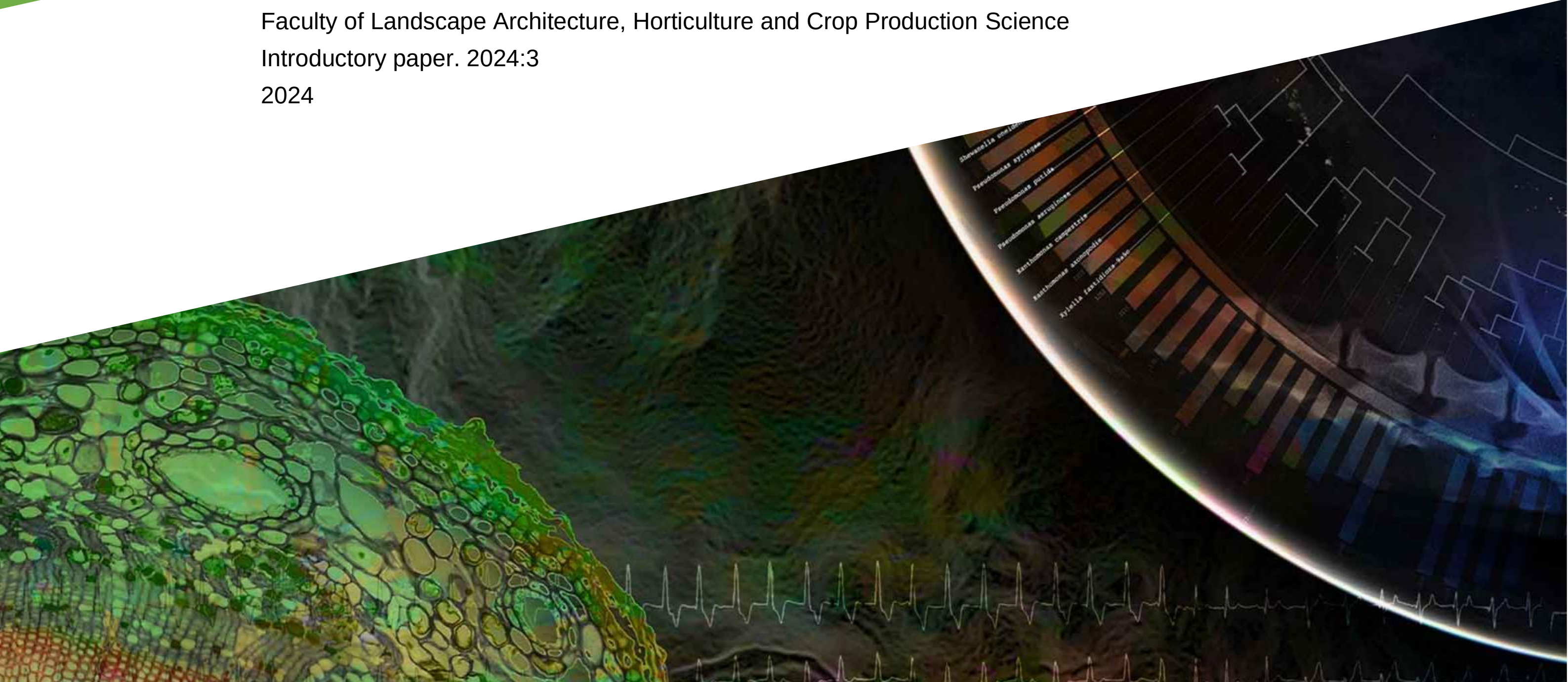

Daylighting and electric lighting for sustainable cattle buildings: A systematic literature review

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Abstract

This review article summarizes the current state of knowledge on daylighting and electric lighting of cattle facilities for sustainable cattle buildings. The literature review covers a total of 54 publications with the aim to determine the extent of current research, identify research gaps, and formulate the most pressing areas for future research. The review process is a Systematic Literature Review (SLR) followed by synthesis and analysis of the findings. The article includes multidisciplinary researches performed in animal and agricultural science, sustainability, architecture, and building science context. The results suggest that daylighting and electric lighting can impact by ensuring improved animal welfare, worker wellbeing, production, and energy efficiency. However, there are still gaps in the research, particularly due to the lack of research taking into consideration both the animal and building science perspective simultaneously. Finally, this review provides insights into the potential benefits and limitations of lighting interventions, while identifying important areas for future research.

Keywords: Cattle barn; Energy efficiency; Sustainable agriculture; Dairy farm environment; Animal building; Livestock welfare.

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Abbreviations

AHP	Analytic Hierarchy Process
GABA	Gamma-aminobutyric Acid
GHG	Greenhouse Gas
LCA	Life-cycle Assessment
LED	Light-emitting Diodes
LPCV	Low Profile Cross Ventilated
LPD	Lighting Power Density
pH	Potential of Hydrogen
PV	Photovoltaic
RTP	Real Time Pricing
SLR	Systematic Literature Review
SWOT	Strength, Weakness, Opportunity and Threat
TOU	Time of Use Tariff
THI	Temperature-humidity index

1. Introduction

Light has a positive impact on milk production (Casey and Plaut, 2022) as well as cattle and human wellbeing (Gentile *et al.*, 2018). Light provided by integration of daylight, modern lighting and advanced controls can lower energy demand in buildings (Gentile *et al.*, 2022; Gentile, Laike and Dubois, 2014; Gentile, Dubois and Laike, 2015). Therefore, daylight utilization and availability of appropriate electric lighting in cattle buildings is a crucial aspect to ensure suitable luminous indoor environment for the animals and humans while ensuring energy efficiency. A study performed in Canada by Houston, Gyamfi and Whale (2014) points out that a reduction in energy use is observed during the summer months compared to winter months in the case building, which is directly related to the length of daylight hours. Switching from fluorescent lamps to Light-emitting Diodes (LED) offers significant advantages, such as the ability to simulate dusk and dawn and adjust the colour of light (Gentile *et al.*, 2022). Additionally, replacing electric lighting by daylighting offers substantial energy savings, while providing flicker-free light and more natural transitions from dusk to dawn.

Lighting in cattle buildings plays a crucial role by maintaining the health, welfare and productivity of the animals. Light has a positive impact by increasing fertility and milk production (Dahl, Tao and Thompson, 2012). A well-designed lighting system can properly regulate the animals' circadian rhythm, leading to improved sleep patterns. This ensures increased milk production and healthier animals (Plaut and Casey, 2012).

The overall goal of this SLR is to understand the definition of sustainable lighting for cattle buildings to satisfy the following research questions:

1. What are the existing knowledge about sustainably lit animal buildings?
2. What are the strengths, weaknesses, opportunities, and threats (SWOT) of lighting in cattle buildings?
3. What are the existing research gaps and key areas for future research when considering both animal welfare and building science in sustainably lit cattle buildings?

To answer these research questions, the subsequent chapters will outline the systematic methodology, present the results, discussions, and ultimately offer conclusions related to daylighting and electric lighting in sustainable cattle buildings.

2. Methodology

2.1 Search framework

A literature search was conducted for this systematic literature review (SLR) to find interdisciplinary research in four areas:

1. Daylighting and electric lighting: The effects of natural and electric lighting within agricultural buildings.
2. Animals: The influence of light and lighting strategies on the welfare and productivity of livestock with a specific focus on cattle.
3. Building and retrofit: The implications of lighting interventions on the design and modification of agricultural buildings.
4. Sustainability and environment: The environmental impact and sustainability of lighting practices in farming operations.

The search was primarily focused on studies that incorporate two or more intersections of these fields. Articles that included all of the four areas were considered most relevant by forming a tertiary intersection of fields. Articles covering three and two areas were considered to form secondary and primary intersections, respectively. Articles that discussed only one area were not considered for the SLR. The search framework is explained in
Figure 1.

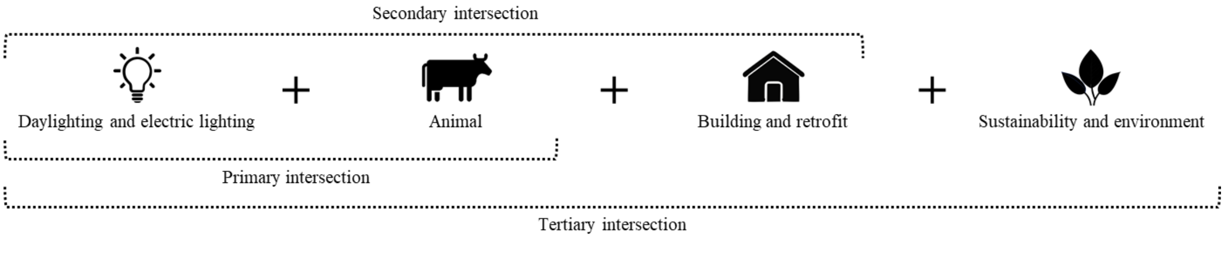

Figure 1: Search framework of the study.

2.2 Search strategy and selection process

The literature search was performed in Scopus, Web of Science, and the GreenFILE database. The databases were chosen based on wide availability of relevant and quality publications. Factors such as research design, methodology, data collection, and analysis methods were considered for quality assessment. The final quality assessment was performed after reading the full-text and determining its relevance to the SLR.

Publications from inception to March 2024 were reviewed. The search included published literature with no language or geographical restriction. Initial search queries were developed as simple sentences such as:

1. Lighting retrofit in animal buildings.
2. Impact of light on animals.
3. Environmental impact of building lighting retrofit.
4. Energy-saving potential of daylight and lighting retrofit.

Important keywords, synonyms, or related terms were extracted from the above sentences. These keywords and terms were used to form search queries to conduct search for titles, abstracts and keywords in databases:

1. Daylight, lighting, electric lighting.
2. Animal, livestock, bovine.
3. Sustainability, energy-efficiency, Life-cycle assessment (LCA), environmental impact.
4. Agricultural buildings, animal buildings.

Four search queries were performed in March 2024 to analyse the number of results. Search queries with too few or too many results were not considered to maintain a scalable study according to the scope of the research. The search queries along with the number of resulting publications in each database is illustrated in Table 1. A snowball method supplemented the original database search, incorporating references from initial papers and relevant studies not found in databases. Selection criteria prioritized journal and conference articles, emphasizing relevance to livestock, particularly cattle. Quality assessment considered research design and methodology. A few publications were also identified from initial screenings and previous project applications concerning lighting in livestock buildings.

Table 1: *Search queries and results in different databases.*

Search Query	Scopus	Web of Science	Green FILE	Total
(sustainab* OR "energy efficien*" OR "life-cycle assess*" OR "environment* impact") AND (daylight* OR light* OR "electric light*") AND ("agricultur* build*" OR "animal build*" OR "livestock build*" OR "bovine build*")	6	5	0	11
(sustainab* OR "energy efficien*" OR "life-cycle assess*" OR "environment* impact") AND (daylight* OR light* OR "electric light*") AND (agricultur* OR animal OR livestock OR bovine) AND (build* OR stable*)	709	387	113	1209
(sustainab* OR "energy efficien*" OR "life-cycle assess*" OR "environment* impact") AND (daylight*) AND (LED OR light* OR "electric light*") AND (agricultur* OR animal OR livestock OR bovine) AND (build* OR stable*)	7	7	1	15
(daylight*) AND (LED OR light* OR "electric light*") AND (agricultur* OR animal OR livestock OR bovine) AND (build* OR stable*)	60	35	6	101
(sustainab* OR "energy efficien*" OR "life-cycle assess*" OR "environment* impact") AND (daylight* OR light* OR "electric light*") AND (animal OR livestock OR bovine OR cow OR cattle OR dairy) AND (build* OR stable* OR barn)	264	118	72	454

Results from the first and third queries were disregarded as they generated very few articles. The second search query was also omitted as it generated many articles including a higher number of irrelevant articles. Results from the final two search queries were screened to find the most relevant publications. The following inclusion criteria were applied to find the relevant publications:

1. Scientific journal and conference articles.
2. Relevance to research area.
3. Studies on humans and animals, with emphasis on livestock, especially cattle.
4. Literature covering at least two of the four specified areas.
5. All geographical locations to understand the impact of different climates and cultures.

The following exclusion criteria were also applied:

1. Books, reports, standards, and webpages.
2. Publications significantly deviating from the subject area.
3. Literature covering only one of the four specified areas.
4. Articles unrelated to agricultural buildings.

The publications gathered from the three databases with the final two queries were investigated for final selection. The list contained a total of 555 articles of which 101 were from the fourth and 454 were from the fifth query. Duplicates were removed first before applying the inclusion and exclusion criteria to select final publications. The reference sections of these finalized publications were further screened in a snowball method to find other relevant publications. However, it is to be noted that a snowball method does not allow to find articles published prior to the first found article. Furthermore, a few publications were gathered from previous research applications, which brought the final number of publications to 54. Figure 2 illustrates the overall publication selection process.

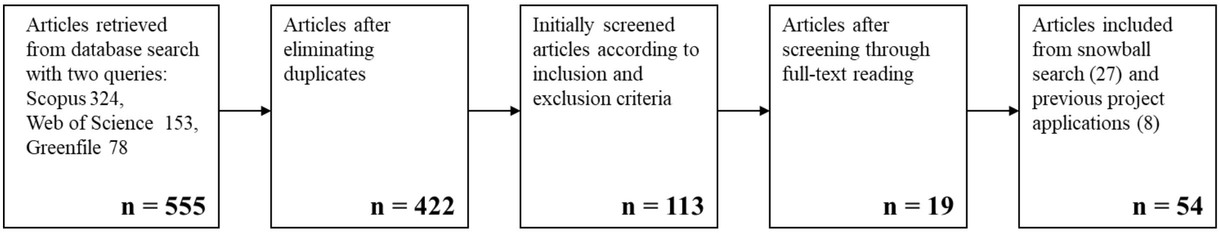

Figure 2: A flowchart depicting the selection process.

After the database and associated search, 54 publications were selected and screened for detailed analysis. The data extracted from the studies included: types of lighting systems, lighting control methods, effect of lighting on cattle behaviour, health, welfare, workers' health and wellbeing, building properties, energy use, retrofit technologies, and sustainability issues. The extracted data were synthesized and analysed to identify key findings and draw conclusions.

3. Results

3.1 General overview of literature selection

The keywords and indexed keywords of all the publications gathered through the last two searches before the screening process were visualized using the program VOSviewer (Van Eck and Waltman, 2023) according to the number of occurrences and co-relations to other keywords (Figure 3). The illustration provides an overview of the subject areas as well as the inter-relations between them. The most commonly occurring words were: animal(s), light/lighting, nonhuman, circadian rhythm, and photoperiodicity.

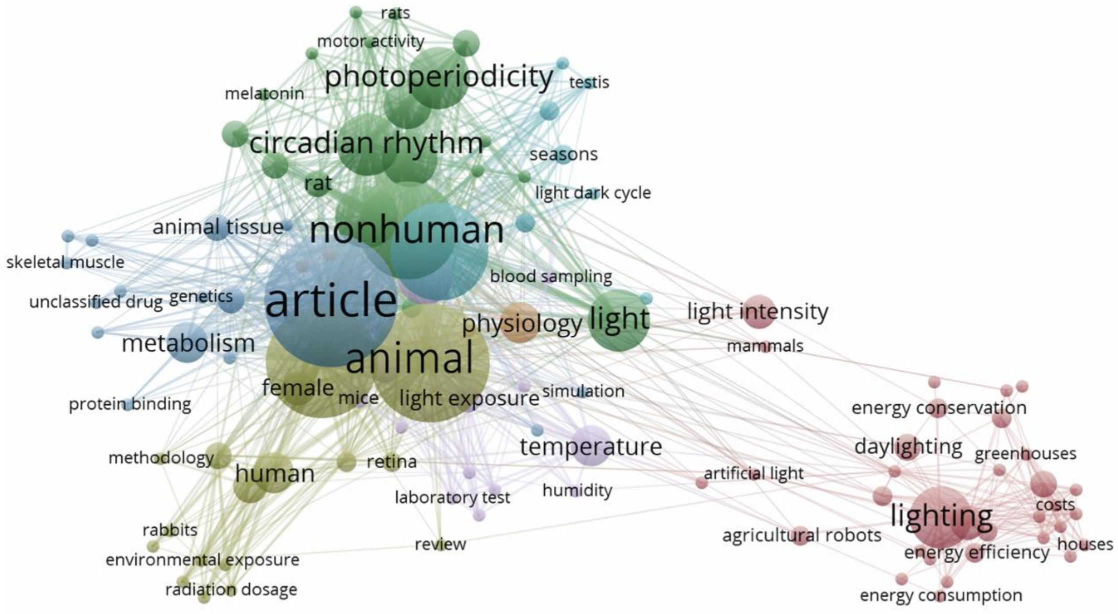

Figure 3: A visualization created using VOSviewer (Van Eck and Waltman, 2023) depicting the occurrence and co-relation between the keywords gathered from the final two database search results.

The geographical and timeline data of the publications found through the Scopus search before the screening process is illustrated in Figure 4 andFigure 5. The highest number of studies were conducted in the USA, while China, Germany, UK, France, and India follow. Sweden shared the 11th position with Canada with only four publications each. Furthermore, the timeline data shows that the earliest studies found in the databases were from the 1970s. A trend of fewer publications per year continued up until the 2000s, followed by a sharp increase in the number of publications up to 2024 which can be attributed to a general increase of scientific publications.

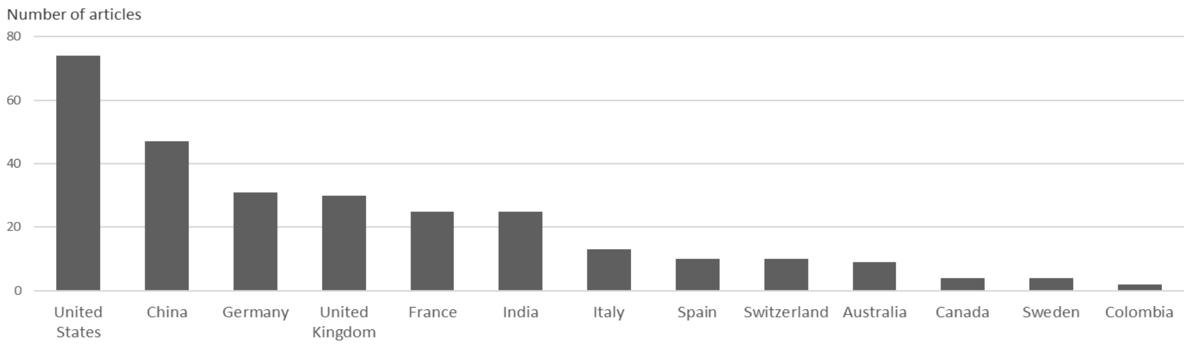

Figure 4: Geographical data of the number of relevant articles found through Scopus database search, graph adapted from Scopus results.

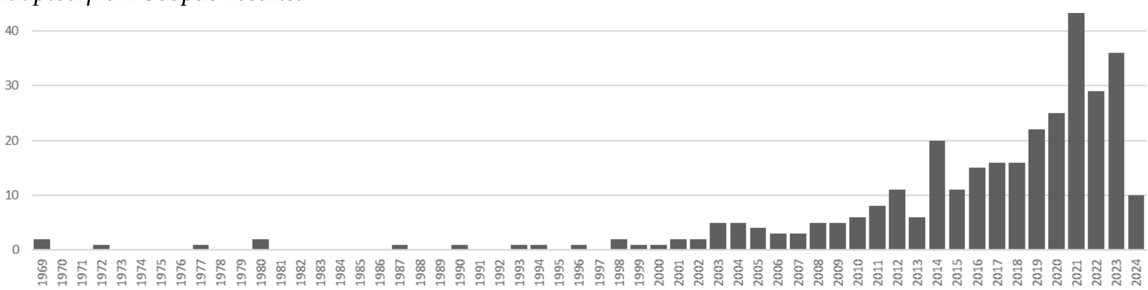

Figure 5: Timeline data of the number of relevant articles found through Scopus database search, graph adapted from Scopus results.

3.2 Summary of the SLR

The final 54 publications were categorized in four different areas and their intersections between subject areas were recorded:

1. Tertiary intersection: Only seven publications discussed all four subject areas.
2. Secondary intersection: 12 publications included three of the areas, forming a secondary intersection.
3. Primary intersection: 35 out of the 54 formed a primary intersection.

The complex nature of these intersections could not be visualized through a typical Venn diagram. Therefore, an elliptical intersection diagram was produced to depict the intersecting fields and the number of publications in each of them (Figure 6).

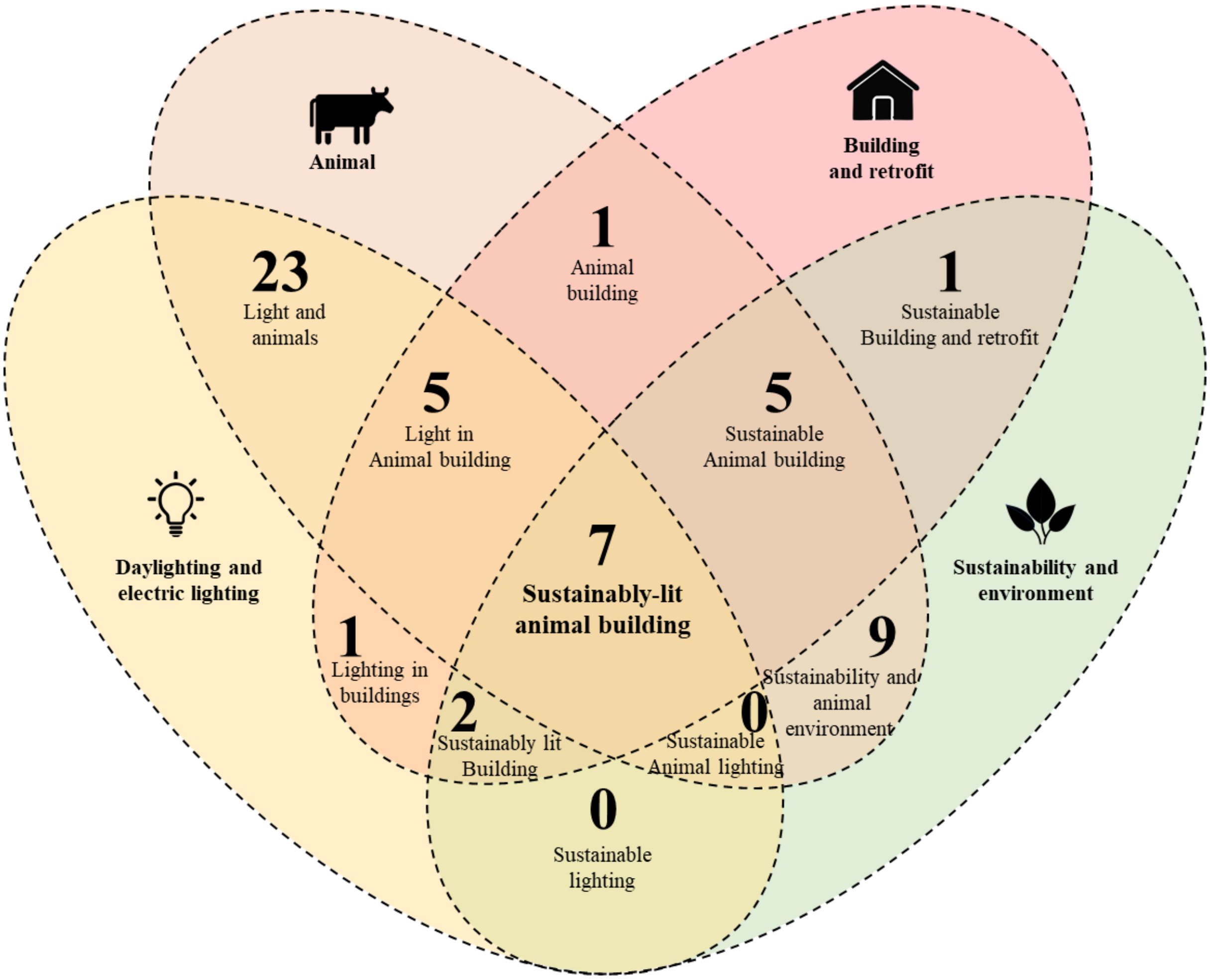

Figure 6: An illustration showing the number of publications in different intersections of subject areas with a total of 54 publications.

An overview of the major findings of this SLR is presented in Table 2.The table includes author and reference year, country or region of research, source, and primary conclusions. The literature is categorized by primary, secondary, and tertiary intersections based on the number of study fields included.

Table 2: Summary of the SLR.

Author and year reference	Country/ Region	Search method	Animals	Method and primary conclusion(s)
Tertiary intersection: Sustainably lit animal buildings (n=7)				
(Dovlatov *et al.*, 2023)	Russia	Scopus	Livestock	**Development of a calculation model.** Highlighted the importance of high-quality, energy-saving LED lighting in agricultural settings. Optimal lighting conditions were identified, considering factors like light intensity and colour temperature, which can enhance the productivity and quality of agricultural products.
(Moerkerken *et al.*, 2021)	Nether-lands	Snowball	Dairy cows	**Statistical analysis of farm energy use dataset.** Solar panels significantly improved energy efficiency in Dutch dairy farms. However, automatic milking systems reduced these energy efficiency gains. Higher milk production volumes also increased energy efficiency.
(Bartkowiak, 2021)	Poland	Scopus	Livestock	**Review.** The artificial lighting should meet the requirements of the animals, provide good working conditions for humans, while being energy-efficient. Suggested energy-saving strategies include replacing conventional light bulbs, using dimmers, lighting controls using sensors or switches, using lighting schemes, introducing photoelectric cells, etc. Specific focus was put on the increasing use of LED lighting due to its reduced CO_2 emissions and presence of no harmful substances such as Mercury.
(Bey *et al.*, 2016)	Algeria	Greenfile	Dairy cows	**Viability study.** With an illumination value ranging between 150-250 lux and installed power of 3.75 W/m^2, the annual energy consumption of a farm decreased by 13% and milk production increased by 8%. A Photovoltaic (PV) system was introduced and the farm transitioned from an electricity consumer with a cost of 27 017€ to an electricity producer with profit of 29 633€.
(Mohsenimanesh *et al.*, 2021)	Canada	Scopus	Dairy cows	**Literature review.** The review found that highest electricity use in dairy farms were for milking (22%) and milk cooling systems (23%). Energy use was lower for pasture-based dairy systems (475 kWh/cow/year) than for confined systems (769 kWh/cow/year). There is potential to reduce electricity demand by one-third by combining several conservation technologies such as milk vacuum pumps, milking systems, fans, pre-cool heat exchangers, refrigeration heat recovery systems, energy-efficient light fixtures (compact fluorescents,

				LED), and high-volume low-speed fans for efficient ventilation.
(Diéguez’ *et al.*, 2016)	Sweden	Scopus	Pigs	**Simulation.** Computer simulations can accurately predict light pipe performance in farm buildings. The accuracy was higher for overcast than clear skies. Factors like solar altitude, reflectance, and roof tilt significantly influenced light output from the pipe.
(Wachenfelt *et al.*, 2015)	Sweden	Previous application	Pigs	**Installation and photometric measurements.** Light pipes in animal houses can significantly reduce electricity use. However, due to low electricity prices at the time of performing the study, the investment was not profitable. The use of light pipes also improved the quality of light for animals.
Secondary intersection 1: Lighting in animal buildings (n=5)				
(Šístková, Peterka and Peterka, 2010)	Czech Republic	Snowball	Dairy cows	**Photometric and sonic measurements.** Lighting and noise conditions in dairy cow buildings were substandard. Poor illumination was identified, especially in winter, along with occasional excessive noise. Suggested improvements were: cleaning light fixtures, more light sources, and sensors.
(Harner, Smith and Janni, 2008)	USA	Snowball	Dairy cows	**Literature review.** Highlighted the significance of lighting in Low Profile Cross Ventilated (LPCV) dairy facilities. It detailed the distinct light requirements for lactating and dry cows and the challenges in meeting these in LPCV buildings. Provided guidelines on lighting design, including illumination levels, system performance, bulb colour characteristics, and fixture placement.
(Balková and Páleš, 2015)	Slovakia	Snowball	Dairy cows	**Photometric measurements.** Skylight material significantly impacts stable lighting. Transparent glass skylights caused overheating in summer. Stable width and shelter presence also affected daylighting levels.
(Balková and Záhorská, 2016)	Slovakia	Snowball	Dairy cows	**Photometric measurements.** Shelter and skylights significantly influenced daylight in dairy cow buildings. Lower light in sheltered areas could negatively impact cow productivity. Suggestions included translucent roofing or artificial lighting.
(Asher *et al.*, 2022)	Israel	Snowball	Dairy cows	**Light treatment.** White LED night lighting altered the milk's fatty acid composition in dairy cows. Natural light-dark cycles resulted in healthier milk fat profiles. The research suggests natural light is better for cow well-being and milk quality.
Secondary intersection 2: Sustainable animal buildings (n=5)				

(Houston, Gyamfi and Whale, 2014)	Canada	Previous application	Dairy cows	**Case study.** Small-scale dairy farms can reduce energy costs through efficiency measures and renewable energy. Upgrading lighting, improving equipment maintenance, and using renewable sources like wind turbines and anaerobic digesters were effective. However, high initial investment costs for wind turbines were a challenge.
(Herrero *et al.*, 2016)	World-wide	Previous application	Livestock	**Literature review.** Livestock production significantly contributes to GHG. Potential mitigation strategies include improving feed efficiency, reducing deforestation, and promoting dietary changes. Challenges in implementing these strategies are related to economic, societal, and food security considerations.
(Matkovi and Tofant, 2006)	Croatia	Snowball	Dairy cows	**Statistical analysis of collected sample.** Microclimate factors influenced bacterial count in a dairy barn. Bacterial count was highest in the evening and decreased with distance from the barn. Emphasized the importance of monitoring these factors for environmental impact.
(Andrade *et al.*, 2020)	Brazil	Snowball	Dairy cows	**Photometric and sonic measurements.** Compared lighting and noise in two types of dairy barns. Found that neither barn met the recommended light intensity for lactating cows. However, noise levels in both barns were within the acceptable range for animal comfort.
(Upton *et al.*, 2015)	Ireland	Web of Science	Dairy cows	**Simulation.** Five different electricity tariffs models were studied: Flat, Day and Night, Time of Use Tariff (TOU1), TOU2 and Real time pricing (RTP). The earliest first milking start time and the latest second milking start time resulted in the lowest energy consumption. TOU2 offered the highest potential for reducing annual electricity costs through adjusting milking start times, accounting for 39%, 34%, and 33% of total costs for small, medium, and large farms respectively. The Flat tariff showed the least potential with only 7%, 5%, and 7% reduction in costs for the respective farm sizes.
Secondary intersection 3: Sustainable lighting for animals (n=0)				
Secondary intersection 4: Sustainably lit buildings (n=2)				
(Ron MacDonald *et al.*, 2008)	USA	Scopus	Turkeys	**Case study.** Electricity use in turkey grower barns was compared with different lighting systems. A 55% energy savings was found when using photocell lighting

				control. The payback period for this system was less than three years.
(Dubois *et al.*, 2015)	Europe	Snowball	-	**Literature review.** Strategies for retrofitting lighting systems to reduce energy use in offices were reviewed. Energy savings from lighting retrofits varied based on the specific strategy and context. The need for more research on the actual energy performance of retrofitted lighting systems was emphasized.
Primary intersection 1: Animal buildings (n=1)				
(Kühl, Gauly and Spiller, 2019)	Germany	Snowball	Dairy cows	**Picture-based interview.** Public acceptance of dairy farming systems was low for indoor systems without outdoor access. The presence of paddocks or pastures significantly increased acceptance by humans. The study emphasized the importance of natural conditions and animal welfare in housing planning.
Primary intersection 2: Light and animals (n=23)				
Sub-category 1: Impact of light on cattle (n=9)				
(Dahl, Auchtung and Reid, 2004)	USA	Snowball	Dairy cows	**Photoperiod manipulation and changing milking frequency.** Long days during lactation increase milk production in cows. Frequent milking improves udder health and milk yield.
(Plaut and Casey, 2012)	USA	Snowball	Dairy cows	**Literature review.** Explored the role of circadian clocks in the mammary gland and milk production in cows. Changes in photoperiod can affect milk yield and quality.
(Dahl, Tao and Thompson, 2012)	USA	Previous application	Dairy cows	**Photoperiod manipulation.** Photoperiod impacts milk production and growth in cows. Long days increase milk yield, while short days boost mammary growth. Photoperiod influences hormone secretion related to lactation.
(Peters *et al.*, 1981)	USA	Previous application	Dairy cows	**Photoperiod manipulation and supplemental light treatment.** Cows exposed to 16 hours of light produced more milk. Light exposure increased the cows' food intake and prolactin levels. Light exposure did not affect growth hormone or milk fat content.
(Hjalmarsson *et al.*, 2014)	Sweden	Snowball	Dairy cows	**Night light treatment.** Explored how night light intensity impacts cow behaviour and milk production. Lower light levels at night did not change cow activity, but reduced milk yield. Night lighting for dairy cows may be more about increasing production than improving welfare.
(Bal *et al.*, 2008)	Canada	Snowball	Dairy cows	**Night light treatment.** Dim light at night does not affect milk yield or composition in lactating cows. Such light

				exposure does not suppress melatonin release. However, dim light slightly increases milk lactose concentration.
(Gavan and Motorga, 2009)	Romania	Previous application	Dairy cows (Holstein)	**Supplemental light treatment.** Holstein cows exposed to supplemental light produced more fat-corrected milk than those with only natural light. Adjusting the photoperiod could be a useful tool for dairy farmers.
(Casey, Plaut and Boerman, 2022)	USA	Snowball	Dairy cows	**Photoperiod manipulation.** Circadian clocks play a crucial role in lactation and mammary gland development. Disruptions can negatively impact production and health.
(Rehkämper and Görlach, 1997)	Germany	Previous application	Bull	**Vision test.** Adult bulls can visually distinguish between different-sized objects but learn slower than calves. Bulls' performance in learning tasks is influenced by their daily temperament. Bulls can use vision to solve problems.
Sub-category 2: Impact of light on mammals and other animals (n=14)				
(Shinde and Gupta, 2016)	India	Previous application	Farm animal and birds	**Literature review.** Light and day length impact physiological processes in farm animals. Manipulating light can enhance production and growth in various species. Melatonin influences reproduction and mammary growth.
(Marín-Doñágueda *et al.*, 2021)	Spain	Scopus	Mammals	**Lighting system design.** Developed a lighting system with adjustable colour temperatures and circadian effects. The prototype showed good performance in terms of colour coordinates and circadian efficacy.
(Bano-Otalora *et al.*, 2021)	UK	Scopus	Diurnal mammals	**Light intensity change.** Increasing daytime light intensity enhances circadian rhythm amplitude in diurnal mammals. Bright light exposure during the day improves circadian rhythm and health.
(Delgadillo *et al.*, 2004)	Mexico	Scopus	Male goats	**Photoperiod manipulation.** Photoperiod influences testosterone secretion and testicular weight in male goats, controlling their breeding season. Genetics also play a role in the timing of reproduction.
(Logan *et al.*, 2020)	Australia	Snowball	Dairy goats	**Photoperiod manipulation.** Extended daylight increases milk production in dairy goats, especially in late lactation. However, it reduces ovulation, which can be partially offset by male goat presence. Extended light may negatively affect goats' reproductive performance.
(Paterson and Pearce, 1990)	Australia	Snowball	Gilts (young female pigs)	**Photoperiod manipulation.** Long daylight hours delay puberty in gilts. Contact with mature boars significantly influences gilts' puberty. Factors like environment and nutrition also affect gilts' reproductive development.

(Jacobs, 2009)	USA	Snowball	Primates	**Literature review.** Explores the evolution and biological mechanisms of colour vision in mammals. Highlights variations in colour vision among species, particularly in primates and platyrrhine monkeys and its role in foraging.
(Farsi *et al.*, 2022)	Morocco	Scopus	Dromedary camels	**Seasonal locomotor and diurnal activity study.** Dromedary camels maintain a consistent daily activity pattern throughout the year. Their activity peaks during the day and is influenced by changes in light intensity. Rainfall can disrupt this pattern, causing unusual night-time activity.
(Ware *et al.*, 2020)	USA	Web of Science	Polar bears	**Collar-mounted accelerometer and global positioning system data.** Polar bears maintain consistent activity patterns throughout the year. Factors like feeding period and reproductive status influence these activity patterns. Polar bears' behaviour adjusts to environmental conditions and prey availability.
(Trivedi, Rani and Kumar, 2006)	India	Scopus	Male sparrows	**Photoperiod manipulation.** Twilight exposure delays testicular regression in male sparrows but does not affect daily activity. Separate processes likely govern sparrows' circadian functions and testicular cycles. Reviewed birds' seasonal responses and photoperiodic control.
(Williams *et al.*, 2017)	USA	Scopus	Arctic ground squirrels	**Surgically implanted loggers.** Arctic ground squirrels maintain daily rhythms despite constant summer daylight. They quickly adjust to natural light changes, but not artificial ones. Low vasopressin expression in their brains may aid this adjustment.
(Yao *et al.*, 2018)	USA/ Canada	Scopus	Mammals	**Measurement of neural activity.** Changes in electrical coupling and Gamma-aminobutyric Acid (GABA) inhibition affect direction tuning in retinal ganglion cells. The balance between motion detection and direction discrimination varies with light levels.
(Polo, Carrascal and Metcalfe, 2007)	Spain	Greenfile	Coat tits	**Photoperiod manipulation.** Coal tits adjust their daily mass gain based on day length. Birds in areas with longer winter days delayed mass gain until late in the day.
(De La Iglesia *et al.*, 2016)	USA	Scopus	Mammals	**Literature review.** Sleep habits have changed with migration for mammals, and sleep duration varies. Chronic sleep restriction and deprivation have negative impacts on neurobehavioral functions and sleep physiology.

Primary intersection 3: Sustainable lighting (n=0)				
Primary intersection 4: Sustainable building and retrofit (n=1)				
(Neves-Silva and Camarinha-Matos, 2022)	Portugal	Snowball	-	**Simulation.** Presented a simulation-based tool for improving energy efficiency in building retrofits. The tool used Analytic Hierarchy Process (AHP) to evaluate retrofit scenarios based on benefits, opportunities, costs, and risks. The effectiveness of the tool was validated through a real business case in Poland.
Primary intersection 5: Sustainability and animal environment (n=9)				
(Collier, Dahl and VanBaale, 2006)	USA	Snowball	Dairy cows	**Statistical analysis.** Environmental factors, particularly heat stress, affect dairy cows' performance and health. Discussed strategies like cooling systems and photoperiod manipulation to improve cattles' heat stress resistance and milk production. Highlighted the potential of genetic research in identifying heat-stress sensitivity and tolerance in dairy cows.
(Srikandakumar and Johnson, 2004)	Oman	Snowball	Dairy cows (Holstein, Jersey, and Zebu)	**Analysis of sample collected during summer and winter.** Heat stress increases body temperature and breathing rate in Holstein, Jersey, and Zebu cows. Holstein cows produce more milk than Jersey and Zebu cows during cooler months. Heat stress affects blood chemistry differently in each breed, notably lowering Potenitial of Hydrogen (pH) in Jersey cows.
(West, 2003)	USA	Snowball	Dairy cows	**Literature review.** Heat stress negatively impacts dairy cows' food intake and milk production. Cooling systems, shade, and nutritional adjustments can mitigate these effects. Genetic selection for heat tolerance can improve cattle's resilience to heat.
(Gantner *et al.*, 2015)	Croatia	Web of Science	Dairy cows (Holstein)	**Statistical analysis.** Temperature-humidity Index (THI) value below 68 did not cause significant change in the first parity Holstein's daily milk production. Significant decrease of daily milk yield was observed at THI value above 68 with estimated drop from 0.240 to 0.716 kg milk/day. The THI value of 68 has been taken as the threshold value for the first parity Holsteins in Eastern Croatia.
(Grandin, 2021)	USA	Snowball	Cattle, pigs, and sheeps	**Literature review.** The environment significantly impacts livestock movement and handling in facilities. Simple changes like lighting and noise reduction can improve animal welfare. Proper training in stockmanship is crucial for effective livestock handling.

(Allen Tucker, 1982)	USA	Snowball	Dairy cows	**Literature review.** Seasonal changes such as temperature and light exposure affect cattle reproduction, growth, and milk yield. Prolactin hormone in cattle is highly responsive to changes in daily light duration. Light variations influence hormone responses in prepubertal bulls and heifers.
(Cardoso *et al.*, 2016)	USA	Snowball	Dairy cows	**Online survey.** Public views on ideal dairy farms prioritize animal welfare. Participants valued sustainable practices and high-quality, organic dairy products. Profitability and efficiency were also important to respondents.
(Dimov, Marinov and Penev, 2020)	Bulgaria	Snowball	Dairy cows	**Literature review.** Dairy farming work conditions significantly impact worker health and safety. Factors like lighting, air quality, and noise levels contribute to occupational diseases. Improving these conditions can enhance workers' well-being.
(P. M. Layde *et al.*, 1996)	USA	Snowball	Dairy cows	**Statistical analysis.** Longer work hours increase the risk of farm animal-related injuries. Males and dairy farm workers are more prone to such injuries. The use of all-terrain vehicles and non-resident workers also contribute to risks.
Primary intersection 6: Lighting in buildings (n=1)				
(Vu *et al.*, 2022)	Vietnam	Web of Science	-	**Optimized daylighting system.** Proposes an optimized daylighting system for indoor farming using plastic optical fiber. The system, tested on an indoor farm, showed high efficiency and significant energy savings. The proposed system is more cost-effective than existing ones.

3.3 Tertiary intersection: Sustainably lit animal buildings

Seven articles discussed all the four study fields among which five were found through the database search. Dovlatov *et al.* (2023) emphasized the significance of high-quality, energy-efficient LED lighting in agricultural settings. They found that optimal lighting conditions, considering factors like light intensity, colour temperature, and operating time, can enhance the productivity and quality of agricultural products. They also discovered that LED lamps emitting red and blue light positively impact milk yields in dairy cows. They developed a method for calculating optimal illumination parameters and proposed a cooling system to prolong the LED's lifespan. Moerkerken *et al.* (2021) found that solar panels significantly improved energy efficiency in Dutch dairy farms using data from 2015 to 2018. However, the introduction of automatic milking systems increased energy use. Twilight switches and time switches were associated with increased energy efficiency. The study suggested that future strategies should focus on promoting energy-efficient automatic milking systems and increasing the use of solar energy on farms.

Bartkowiak (2021) discussed the importance of energy-efficient and low-emission livestock buildings in smart farming for sustainable agricultural practices. He emphasized using modern solutions like sustainable lighting to reduce energy consumption, operating costs while ensuring animal welfare. Sustainable lighting options like LED lamps, dimmers, and programmable timers were highlighted for improving animal welfare, reducing energy consumption, and enhancing productivity. Bey *et al.* (2016) explored the optimization of a photovoltaic system in Algerian dairy farms to reduce energy consumption. Through computational optimization, the study showed that implementing photovoltaic systems can significantly decrease energy consumption, while maintaining higher milk production, and reduce CO_2 emissions, making the dairy farm an electricity producer with less environmental impact. The study linked optimized lighting ranging between 150-250 lux with improved milk production. Mohsenimanesh *et al.* (2021) discussed the impact of energy-efficient lighting in dairy barns on electricity use and milk production. Their study suggested that pasture-based dairy systems used less electricity than barn-based systems. According to these authors, electricity demands can be reduced by one-third by combining several conservation technologies. In addition to conservation technologies, dairy farms can reach net zero status by including renewable energy production.

Diéguez' *et al.* (2016) evaluated the use of computer simulations to predict light pipe performance in farm buildings for pigs. They found that the simulations accurately predicted illuminance levels compared to measurements, particularly under overcast skies. Key factors influencing light output were identified, including solar altitude, reflectance, and roof tilt. The study also suggested that light pipes perform better in sunny climates with higher solar altitudes. In a further study, Wachenfelt *et al.* (2015) found that light pipes could significantly reduce energy use in South Sweden, with savings ranging from 48% to 55%. The light pipes also provided a continuous spectrum of daylight, improving the light quality for the animals. However, due to low electricity prices, the investment in light pipes was not financially profitable. The study suggested further energy savings could be achieved by combining light pipes with dimmable LED lights and accepting lower daylight illumination levels in certain areas.

In summary, the articles in the tertiary intersection provides the following insights:

1. High-quality, energy-efficient LED lighting improves productivity, with red and blue LEDs boosting milk yields in dairy cows.
2. Energy-efficient livestock buildings with lighting systems such as LED lamps and programmable timers can reduce energy consumption, costs, and emissions while improving animal welfare and productivity.

3. Light pipes can significantly cut energy use by providing natural daylight, but financial benefits are limited in regions with low electricity prices. Combining them with dimmable LEDs can enhance savings.

3.4 Secondary intersection

Articles that discussed at least three of the four study fields were considered to form a secondary intersection:

1. Lighting in animal buildings: All the five articles were derived from the snowball search.
2. Sustainable animal buildings: Five articles discussed sustainable animal buildings.
3. Sustainable lighting for animals: No article exclusively discussed this topic, although the topic was briefly discussed in the articles included in the tertiary intersection.
4. Sustainably lit buildings: One article from Scopus and one article from the snowball method were included.

3.4.1 Lighting in animal buildings

Šístková, Peterka and Peterka (2010) examined light and noise conditions in dairy cow buildings, finding them to be below health standards. They identified poor illumination, particularly during winter, and occasional excessive noise levels that could potentially harm both humans and cows. They suggested improvements such as cleaning fluorescent luminaires, installing additional light sources, and incorporating a light sensor device to enhance the lighting system. Harner, Smith and Janni (2008) underscored the crucial role of appropriate lighting in LPCV dairy facilities. They elaborated on the distinct light requirements for lactating and dry cows and the challenges in fulfilling these in LPCV buildings. They also provided comprehensive guidelines on lighting design, including factors such as illumination levels, system performance, bulb colour characteristics, and fixture placement. Additionally, they discussed how mounting height and roof slope can influence the type of fixtures used, and provided information on lumens, lamp life, and necessary safety and electrical codes.

Balková and Páleš (2015) examined the impact of different materials used for stable cover shells on lighting. It was found that roof skylights significantly influenced lighting, with transparent glass causing overheating in summer. The researchers suggested using translucent glass or adjusting the ceiling structure to improve lighting. They also expressed that the width of the stable and the presence of a shelter could affect light levels. They highlighted the need for a uniform distribution of natural light in stables. Balková and Záhorská (2016) examined the impact of an exterior shelter used as a shading device and skylights on daylight in dairy cow buildings. They found that both elements significantly affected the amount of daylight, with lower illuminance values in sheltered areas. This could potentially alter the cows' locomotion patterns and reduce productivity. Despite the sheltered area meeting minimum light requirements, the daylight factor values were insufficient in the living areas. The shelter provided protection from direct sunlight and overheating but decreased daylight uniformity.

They suggested potential solutions such as using a translucent sail for roofing the shelter or adding artificial lighting with a light sensor device to improve illuminance.

Asher *et al.* (2022) found that while LED lighting did not affect milk production compared to a natural light-dark cycle, it increased the percentage of saturated fatty acids in day milk compared to unsaturated fatty acids, thus producing less healthy milk. The research also revealed that natural light-dark cycles resulted in higher levels of unsaturated fatty acids during daytime milking. It suggested that providing 125 lux of illuminance through white LED at night could yield healthier milk.

The articles provide these major takeaways:

1. Dairy cattle buildings often have poor lighting and excessive noise. Improvements include cleaning lights, adding more light sources, and using light sensors.
2. Proper lighting is crucial for dairy cows, with different needs for lactating and dry cows. Guidelines cover illumination levels, colour, and fixture placement.
3. Roof skylights affect lighting in cattle buildings. Transparent glass can cause overheating while translucent glass or structural changes in the ceiling can help distribute light evenly.
4. LED lighting increases saturated fatty acids in milk compared to natural light-dark cycles which helps to produce healthier milk with more unsaturated fatty acids.

3.4.2 Sustainable animal buildings

Houston, Gyamfi and Whale (2014) evaluated energy efficiency and renewable energy generation opportunities for small-scale dairy farms in Prince Edward Island, Canada. They found that energy use could be significantly reduced through lighting retrofitting, regular maintenance of refrigeration units, and implementation of a lighting control system. Renewable energy generation through wind turbines and anaerobic digesters was found to be feasible. However, the high initial investment cost for the wind turbine was a challenge. Herrero *et al.* (2016) found that livestock production contributes significantly to global GHG emissions, where cattle production systems are the largest contributors. It projected an increase in these emissions, particularly from animal feed production and enteric fermentation. This article explored potential mitigation strategies, including improving feed efficiency, reducing deforestation, and promoting dietary changes.

Matkovi and Tofant (2006) investigated the impact of microclimate on bacterial count and other airborne emissions in general in a dairy barn near Zagreb, Croatia. They found that air temperature, relative humidity, sunlight, and air flow velocity significantly influenced the bacterial count, which was highest in the evening. Andrade *et al.* (2020) compared lighting and noise levels in two types of dairy barns: a climate-controlled and a naturally ventilated compost barn. They found that the naturally ventilated barn had higher light intensity, but neither barn met the recommended light intensity for lactating cows. Noise levels in both barns were within acceptable ranges for animal comfort, although the climate-controlled barn had slightly higher sound pressure. The study concluded that improvements should be made to the lighting conditions in the climate-controlled barn, and additional lighting should be installed in compost barns to maintain optimal light intensity.

Upton *et al.* (2015) discussed the impact of electricity tariffs and milking times on dairy farm energy costs. It highlighted that choosing tariffs with low off-peak rates can result in financial savings, especially for large farms. Adjusting milking times can reduce electricity consumption. The results suggested that both electricity consumption and costs decreased when milking started earlier in the morning and later in the evening.

In summary, these articles provide certain key information:

1. Small-scale dairy farms can save energy with lighting upgrades and using lighting control systems.
2. Livestock production significantly contributes to global GHG emissions, especially cattle.
3. Microclimate factors in dairy barns, such as temperature and humidity, affect bacterial counts.
4. Naturally ventilated barns have higher light intensity but need lighting improvements for optimal cow comfort.

3.4.3 Sustainably lit buildings

Ron MacDonald *et al.* (2008) presented a study on a daylight harvesting system for livestock and poultry. They compared the electricity use of a dimmable fluorescent light system with and without photocells. The results demonstrated that the use of photocell lighting control led to a significant reduction in electricity use, with savings of up to 55%. Furthermore, the payback period for this system was less than three years. The authors concluded that daylight harvesting could be a viable option for other poultry and livestock facilities that have sufficient ambient light levels.

Dubois, Bisegna, *et al.* (2015) reviewed research articles on retrofitting lighting systems in buildings to reduce energy use. They found that energy savings from such retrofits varied greatly depending on the specific strategy and context. Their study highlighted that net energy savings were about 70% of the gross lighting energy savings in most cases. However, they also noted an increase in heating demand connected to lighting retrofits, suggesting that lighting improvements should be combined with building envelope improvements.

3.5 Primary intersection

There were six primary intersections between the four subject areas:

1. Animal buildings: One article exclusively discussed animal buildings, without discussing any sustainability or lighting related issues.

2. Light and animals: A total of 23 articles discussed the impact of lighting on animals, which is the highest among all the intersections covered in this SLR. Ten of these publications were conducted in the USA. Ten articles were found through the database search, five from the snowball search, and eight from screening previous project applications.
3. Sustainable lighting: No article was found specifically on this topic.
4. Sustainable building and retrofit: One article discussed this topic derived from the snowball search.
5. Sustainable animal environment: Nine articles were included in this SLR, among which eight were found through the snowball search method. The majority i.e., six studies were conducted in the USA.
6. Lighting in buildings: One article derived from the database search were included.

3.5.1 Animal buildings

A study by Kühl, Gauly and Spiller (2019) analysed general public acceptance of different husbandry systems for dairy cattle using a picture-based approach. The study found that public acceptance was low for indoor systems without outdoor access, but increased significantly when paddocks or pastures were included. The absence of natural environment indoors was a major reason for low acceptance rates. The evaluation of pictures also showed that positive perceptions were influenced by factors such as freedom of movement, space, cleanliness, and absence of concrete flooring. Overall, the study highlighted the need to consider animal welfare and public perception in building planning.

3.5.2 Light and animals

Impact of light on cattle

The SLR indicates that the impact of light on animals has gained attention in recent years. Nine of the reviewed articles specifically focused on the impact of light on cattle. Dahl, Auchtung and Reid (2004) found that 16-18 hours of light during lactation increase milk production, likely due to higher levels of IGF-I hormone. Short days during the dry period enhance milk production in the subsequent lactation by increasing mammary cell differentiation. Plaut and Casey (2012) found that changes in photoperiod, or the length of daylight, can affect milk yield and quality by influencing clock gene expression. Dahl, Tao and Thompson (2012) observed that long days with 16-18 hours of light stimulate lean growth and increase milk yield, while short days with 8 hours of light during the dry period enhance mammary growth and immune status, leading to increased milk production in the next lactation, a result which is in line with earlier findings. Photoperiod also affects hormone secretion, including prolactin and IGF-I, which are crucial for lactation. Peters *et al.* (1981) found that cows exposed to 16 hours of light daily produced approximately 7% more milk and had increased food intake compared to those only exposed to natural light. This increase in milk production was not affected by the stage of lactation. The light exposure also led to higher levels of prolactin, a hormone that stimulates milk production. However, the light exposure did not affect the levels of growth hormone or the fat content of the milk. The level of light during the experiments were not specified in the above mentioned articles.

Hjalmarsson *et al.* (2014) revealed that reducing night light intensity to 11 lux did not alter the cows' general activity. However, it did lead to a decrease in milk yield. Bal *et al.* (2008) found that dim light exposure did not suppress melatonin release or significantly affect milk yield or composition. However, a slight increase in milk lactose concentration was observed. Gavan and Motorga (2009) found that cows exposed to supplemental light produced more fat-corrected milk than those exposed only to natural light. Casey, Plaut and Boerman (2022) highlighted how disruptions to the circadian rhythm negatively impact milk production, maternal metabolism, and overall maternal health. Rehkämper and Görlach (1997) found that bulls can visually distinguish between different-sized objects, but they learn these tasks more slowly than calves. It was observed that bulls can remember learned tasks and use their vision to solve problems. The use of either the frontal or lateral visual field depended on the bull's disposition.

A closer look into the impact of light in the articles above provide valuable insight for dairy farms for better production and animal welfare:

1. Controlling the duration of daily light exposure enhances milk production, welfare and health.
2. Disruptions in circadian rhythms have implications for metabolic health in dairy cows.
3. Providing night light to dairy cows is more closely related to production levels than animal health.
4. The specific impact of dim light at night on lactation performance remains unclear and requires further research.

It is to be noted that, although light can impact milk production and quality, it cannot be directly related to better welfare for the cows. More research is required to investigate if adjusting to the lighting conditions and higher milk production causes increased pressure on the animals.

Impact of light on mammals and other animals

The impact of light on farms animals in general and others animals have also been discussed in the reviewed articles. Shinde and Gupta's (2016) study on the significant role of light and photoperiod in the physiological processes of farm animals and birds revealed that the length of day and night can influence reproduction, milk production, hormonal response, growth, and behaviour in various species including cows, poultry, sheep, goats, rabbits, and pigs. This article also highlighted the potential of light manipulation as a tool to enhance production and growth in these species. Marín-Doñágueda *et al.* (2021) presented a farm animal lighting system with adjustable colour temperatures and circadian effects, optimized for a balance between image and non-image forming effects of light. The prototype, using white and monochromatic LEDs, demonstrated a strong performance in colour reproduction and circadian function resulting in enhanced sleep quality in mammals. Bano-Otalora *et al.* (2021) examined the impact of daytime light intensity on circadian rhythms in diurnal mammals and found that increasing daytime light intensity enhanced the reproducibility and robustness of circadian rhythms and increased the amplitude of circadian rhythms in the suprachiasmatic nucleus (SCN) activity. Overall, the findings suggest that enhancing indoor lighting or spending time outdoors could have therapeutic benefits for circadian health.

Delgadillo *et al.* (2004) investigated the role of photoperiod in controlling the reproductive seasonality of male goats in subtropical Mexico. They found that photoperiod influenced the annual changes in testosterone secretion, testicular weight, and body weight in male goats. Specifically, testosterone secretion and testicular weight increased during short days and decreased during long days. These changes were consistent across different experimental groups, indicating that photoperiod is a primary factor regulating the breeding season. Additionally, the study suggested that genetics may also play a role in the timing of reproduction. Logan *et al.* (2020) found that extended daylight increases milk production in dairy goats, particularly in the later stages of lactation. However, this extended photoperiod also reduces ovulation rates, which can be partially mitigated by the presence of male goats. Paterson and Pearce (1990) investigated the impact of photoperiod, boar contact, and other factors on the onset of puberty in young female pigs or gilts. They found that long daylight hours, similar to summer conditions, delayed puberty in gilts, while shorter daylight hours stimulated it. Other factors such as the gilts' environment, nutrition, and daily movement also influenced their reproductive development.

Jacobs (2009) investigated the evolution and biological mechanisms of colour vision in mammals. He highlighted the variations in colour vision among different species, with a special emphasis on primates and platyrrhine monkeys. The study suggested that primates' trichromatic colour vision may be linked to their fruit-based diet and the need to distinguish ripe fruits. It also indicated that trichromatic monkeys are more efficient at gathering food based on colour cues. Farsi *et al.* (2022) investigated the daily activity patterns of dromedary camels in different seasons and found that camels maintain a clear 24-hour activity rhythm throughout the year, with activity peaking during the day and dropping at night. The start and end of this active phase coincided with sunrise and sunset, and the duration of activity was linked to seasonal changes in daylight. The study concluded that the camels' activity pattern is primarily driven by changes in light intensity at dusk and dawn, rather than temperature. Ware *et al.* (2020) examined the circadian rhythms of free-ranging polar bears in the Arctic over an 8-year period and found that most polar bears maintain rhythmic activity throughout the year, despite the constant Arctic conditions. However, their activity patterns shift during the spring feeding and seal pupping season. The research also revealed that factors such as feeding period, reproductive status, and habitat influence these rhythms.

Trivedi, Rani and Kumar (2006) explored the impact of twilight exposure on the timing of testicular regression and daily activity rhythm in male house sparrows. They reviewed various studies on the seasonal responses and photoperiodic control in birds, discussing the role of melatonin, testosterone effects, day length perception, and light intensity's influence on circadian rhythms. Williams *et al.* (2017) investigated the circadian rhythms of Arctic ground squirrels (AGS) in constant daylight during summer. Even during constant daylight, AGS maintained daily physiological and behavioural rhythms, rapidly adjusting to natural light changes but remaining insensitive to artificial light-dark transitions. The findings indicate that AGSs' circadian system is more sensitive to natural changes in light intensity, colour temperature, and ambient temperature, which may be a physiological adaptation to the Arctic environment. Yao *et al.* (2018) investigated the role of electrical coupling and GABA inhibition in the direction selectivity of retinal ganglion cells (DSGCs) in mice. The findings provide insights into how the retina adapts to different lighting conditions and the trade-off between motion detection and direction discrimination in DSGCs. Polo, Carrascal and Metcalfe (2007) found that birds in areas with shorter winter days gained bodyweight steadily throughout the daylight hours, while birds in areas with longer winter days grew slower in bodyweight until late in the day. These patterns were found to be dependent on environmental conditions.

De La Iglesia *et al.* (2016) challenged the idea that sleep duration has remained constant throughout human history, arguing that sleep habits have changed as humans migrated to different environments. The study found that chronic sleep restriction and total sleep deprivation had negative effects on neurobehavioral functions and sleep physiology. It suggested that chronic sleep restriction and deprivation can have detrimental impacts on both cognitive function and sleep patterns.

Although not directly related to cattle, the studies discussing the impact of light on mammals and other animals provide some valuable insights:

1. Light impacts farm animals' reproduction, milk production, growth, and behaviour.
2. Light manipulation can enhance production and growth.
3. Better lighting systems and more daylight improve animal circadian rhythms and seasonal activities.

3.5.3 Sustainable building and retrofit

Neves-Silva and Camarinha-Matos (2022) introduced a simulation-based decision support system for enhancing energy efficiency in building retrofits. The system uses real usage data and the AHP to predict post-retrofit scenarios and guide investment decisions. The AHP prioritizes retrofit options based on benefits, opportunities, costs, and risks (BOCR). The system was tested and validated in a real business case in Poland, demonstrating its effectiveness in selecting optimal retrofit solutions. This article also discusses the potential of using a Digital Twin concept for future work, which is a digital representation or replica of the physical building.

3.5.4 Sustainability and animal environment

Collier, Dahl and VanBaale (2006) investigated the environmental impacts on dairy cattle, particularly heat stress causing increased metabolic heat output. They discussed the acclimation process to thermal stress and potential endocrine modifications to improve resistance. They highlighted the negative effects of heat stress on reproductive performance and suggested cooling strategies to improve conception rates in the cows. This article emphasized the importance of shade and cooling systems for cow comfort and milk production. Srikandakumar and Johnson (2004) investigated the impact of heat stress on Holstein, Jersey, and Australian Milking Zebu cows. They found that heat stress increased rectal temperature and respiratory rate in all breeds. However, Holstein cows produced more milk than the other breeds during cooler months. This study also revealed that heat stress affected blood chemistry differently across the breeds. While Holstein and Zebu cows maintained their acid-base balance with minor pH changes during heat stress, Jersey cows experienced a significant reduction in pH. These findings suggest that different cow breeds respond differently to heat stress, with potential implications for milk production and animal health. According to West (2003), heat stress significantly affects dairy cows' feed intake and milk production, especially in hot, humid climates like the south-eastern United States. Their study suggests that implementing cooling systems, providing shade, and making nutritional adjustments can help lower body temperature and improve intake. The research emphasizes the importance of managing heat stress to optimize milk production and maintain profitability for dairy farms. Gantner *et al.* (2015) investigated the relationship between heat stress and milk production in Holstein cows. The data collected between 2006 and 2012 shows that Temperature-heat Index (THI) values below 68 did not cause significant changes in the daily milk production. However, for THI values over 68 caused a significant drop in milk production with an estimated drop ranging from 0.24 to 0.72 kg/cow, day.

Grandin (2021) suggested that simple modifications, such as improved lighting, noise reduction, and non-slip flooring, can enhance animal welfare. Her study also underscored the importance of proper stockmanship training and the role of visual and auditory stimuli influencing animal behaviour. She further discussed the role of facility design, ventilation, and the behaviour of both stock people and animals in low-stress handling. Allen Tucker (1982) discussed the impact of seasonal changes, particularly temperature and light exposure, on cattle reproduction, growth, and milk yield. High temperatures can extend the oestrous cycle, reduce fertility, and increase embryonic mortality. Photoperiod also influences growth rates and milk production. Changes in daily light duration significantly affect prolactin secretion in cattle, which may influence their health. On the other hand, continuous illumination does not maintain high prolactin secretion rates.

Cardoso *et al.* (2016) aimed to understand public perceptions of the ideal dairy farm. They found that people not affiliated with the dairy industry prioritize animal welfare, expressing concerns about the animals' quality of life and its impact on milk quality. Participants also highlighted the importance of sustainable practices, profitability, and efficiency. They preferred organic systems, smaller family operations, and rejected the use of antibiotics and hormones. This study suggests that ensuring animal welfare, incorporating pasture access, and producing healthy products without relying on antibiotics or hormones can improve the social sustainability and public acceptability of the dairy industry.

Dimov, Marinov and Penev (2020) identified physical strain, poor lighting, microclimate, air quality, and noise levels as significant factors contributing to occupational diseases in dairy farms. This article emphasized the importance of adequate lighting for safety and proper ventilation to prevent harmful gas impurities. They also noted that noise can be a stress factor for both animals and human caretakers. This article suggested that addressing these issues can improve the well-being of workers, make the profession more attractive, and enhance animal welfare. Layde *et al.* (1996) found that longer work hours for caretakers in farm buildings significantly increase the risk of farm animal-related injuries, especially in male workers. The most common injuries were strains, sprains, fractures, and bruises, with cows being the most common animal involved. Other factors such as the use of all-terrain vehicles (ATVs) and employing non-resident workers were also associated with higher risks. However, these factors did not reach statistical significance.

The findings from these articles can be summarized for a better understanding:

1. Heat stress in dairy cows lowers milk production and affects their health. Cooling systems and shade are crucial to improve comfort and productivity.
2. Different cow breeds react differently to heat stress, impacting their milk production and health uniquely.
3. Simple changes like better lighting, less noise, and non-slip floors can improve animal welfare.

3.5.5 Lighting in buildings

Vu *et al.* (2022) presented an optimized daylighting system for indoor farming using plastic optical fibre and Fresnel lenses. The system was tested and showed high efficiency and significant energy savings compared to LED lighting. The system was found to be cost-effective compared to existing daylighting systems, indicating potential for commercialization and large-scale implementation.

4. Discussions

The SLR on daylighting and electric lighting for sustainable cattle buildings found a lack of relevant articles that met the inclusion and exclusion criteria in the Scopus, Web of Science, and Greenfile databases (Figure 2). The occurrence and correlation between the keywords are low, indicating that the related research fields don't always interact with each other (Figure 3). Articles that discuss light, photoperiodicity, and circadian rhythms for animals rarely address topics such as lighting design, daylighting, and energy efficiency. While researchers identify what is lacking and needed for the animals, they don't usually explore how to solve these issues through research and design. This can be particularly attributed to the lack of researchers working in the intersection of agricultural and building design. This led to fewer relevant articles that fit the criteria outlined in this review. Although there has been an increase in research in this field over the years (Figure 5), certain geographical regions lag behind. High latitude countries where the lack of daylighting is a challenge for both animals and humans are behind in the number of articles, with Canada and Sweden jointly holding the 11th spot (Figure 4).

4.1 Research question 1: Existing knowledge about sustainably lit animal buildings

The articles included in this SLR discussed a wide range of areas. Figure 7 illustrates the occurrence of these topics in the articles. The impacts of photoperiod and circadian rhythm on animals are widely discussed with significant focus on optimizing light treatment for enhancing overall animal health and welfare. Studies have also extensively explored how lighting affects milk production and quality, indicating its importance in dairy farming. Energy-efficiency is another critical area that highlights the need for sustainability and economic viability. Several researches were found regarding new technologies aiming to improve lighting conditions and overall environment in animal buildings. However, there is lack of significant research-based knowledge in some areas. There is limited discussion on workers' health and welfare, animal building standards and regulations, and the environmental impacts of lighting systems. Buildings' impacts on heat stress and the specific needs of animal vision are comparatively less frequently addressed despite their importance in comprehensive animal care. The geometry and materials of buildings including orientation, window size and placement, ceiling heights etc. as well as overall lighting conditions are also less explored. These findings indicate that there are potential gaps of knowledge in ensuring optimal environments for both animals and workers.

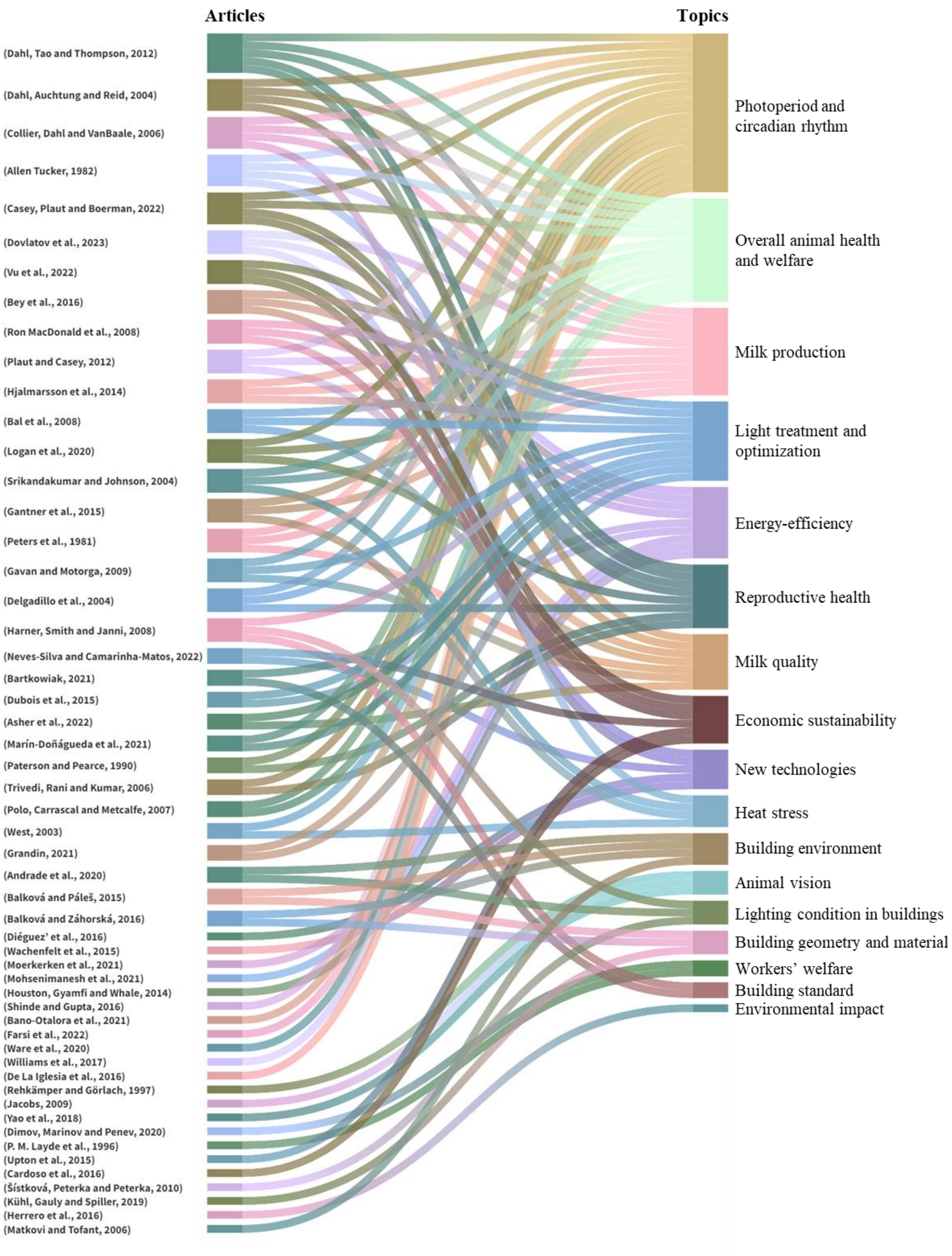

Figure 7: A diagram illustrating different topics discussed in the SLR.

4.2 Research question 2: SWOT analysis of lighting interventions in cattle buildings

The strengths, weaknesses, opportunities and threats related to lighting interventions in cattle buildings are presented in Table 3.

Table 3: SWOT analysis of lighting interventions in cattle buildings.

Strengths	Weaknesses
Improves animal welfare	High initial cost of installation
Improves productivity and milk quality	Maintenance and operational costs
Enhances energy efficiency	Complexity in retrofitting existing buildings
Positively affects worker well-being	Lack of building regulations and standards
Ability to simulate natural light conditions	Limited existing research
Reduces emissions	
Opportunities	**Threats**
Development of cost-effective lighting solutions	Technological obsolescence
Advances in sustainable building designs	Resistance to change from traditional practices
Potential for multi-disciplinary research	Risk of inadequate implementation
Improved public perception and social sustainability	Climate vulnerability
Better building regulations and standards	

4.3 Research question 3: Existing research gaps and areas of future research

The following research gaps were found through this SLR:

1. Holistic studies including both agricultural and building design perspectives
2. Interdisciplinary collaboration
3. Long-term effects of lighting interventions on cattle health and welfare
4. Workers' overall health and welfare in agricultural context
5. Lack of building rules and regulations specific to agricultural and animal building context
6. Research and innovations regarding innovative lighting solutions and new building geometries

This study indicates the potential for certain areas of future research to ensure sustainably lit animal building design practices:

1. Sustainable lighting and building design solutions for animals and humans
2. Interaction between agriculture and building design sectors
3. Multi-disciplinary research projects
4. Public perception and social sustainability
5. Improved building rules and regulations to ensure animals' and workers' health

5. Conclusion

The objective of this SLR was to investigate the state of the art in the field of daylighting and lighting in cattle buildings, while determining which areas of this field have received the most attention. It suggests that proper lighting can positively influence the behaviour, health, welfare, and productivity of cattle, while contributing to the well-being and safety of workers in the facility. The design of the stables including building orientation, window placement, and ceiling height influences the amount and quality of natural light entering the space. Although daylighting plays a crucial role to supplement electric lighting as well as contributes to better animal health, it was often found that many stables rely almost completely on electric lighting. While this is not the best practice to safeguard animal health and welfare, this also puts a negative impact on economic and environmental sustainability. There is evidence that retrofitting existing cattle buildings with improved daylight harvesting, ventilation, and artificial lighting solutions can have a positive impact on cattle welfare, productivity, and energy efficiency while improving thermal comfort during summer. However, retrofitting can also be a complex and costly process, where energy efficiency and sustainability issues must also be considered.

Despite the significant amount of research on lighting in cattle buildings, there are still some gaps in certain areas of the research field such as animal vision, impact of building geometry and materials, lighting conditions in buildings, workers' health and welfare etc. The inter-relation between the keywords used in the reviewed articles indicates a clear distinction between different clusters of research areas having extremely weak linkage between them. This indicates that there is a lack of collaborative researches between different fields.

There is a lack of extensive studies that evaluate the combined impact of electric lighting and daylighting strategies on energy use, animal welfare and productivity. The long-term effects of various lighting systems on animal behaviour, health, and overall performance require further exploration. The lower number of publications in the tertiary intersection area indicates that there is lack of holistic research in this specific field. This can be partially attributed to the lack of interdisciplinary studies done in the fields of agriculture and building design. There are still gaps in research due to the lack of studies taking into consideration both the animal and building science perspective simultaneously. Considering the multifaceted character of this topic, researchers with different backgrounds such as architects and engineers, sustainability specialists, and animal scientists should be involved in multi-disciplinary projects.

Future researches should focus on developing sustainable lighting solutions that not only meet the welfare needs of cattle, but also consider issues such as energy efficiency, heat stress, working environment, and environmental impact. Future studies investigating the interaction between lighting, building design and animal behaviour in cattle buildings are essential for advancing our understanding of how lighting can be optimized to benefit both animals and humans in agricultural context.

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