Geographical trends for automatic milking systems research in non-pasture-based dairy farms: A scoping review

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ABSTRACT

Automatic milking system (AMS) adoption in the United States is trending upward, with issues such as lower availability and increased cost of labor being factors frequently listed as motives for AMS implementation. In addition, more interest in precision dairy farming by the new generation of farmers may also help increase AMS adoption. The objective of this scoping review was to characterize the nature of the literature investigating non-pasture-based AMS and the opportunities and challenges for future research. The eligibility criteria included studies published in or after the year 2000, with at least 500 words, examining various outcomes related to AMS in non-pasture-based dairy farms. Six electronic databases were searched: Biosis (Web of Science), CAB Abstracts (CAB Direct), Medline (PubMed), PubAg, AGRIS (FAO), and Scopus (Elsevier). The review focused on studies with objectives, characteristics, farms, and AMS information. A total of 4,292 titles and abstracts were screened, and 536 studies were finally included. Most of the studies were conducted in Europe (73.5%), among commercial herds (67.9%), comprising Holstein cows (57.7%), using Lely and DeLaval brands (45.4% vs. 39.7%), with free-flow traffic (52.7%). The main research topics investigated were milk production, milk composition, and AMS efficiency, followed by behavior and welfare, health disorders (especially mastitis), and nutrition in Europe and other regions. At the same time, in the United States, trends were similar, except for nutrition. Since 2016, there has been an increased interest in studies on energy and water consumption, technological development, environment (enteric emissions), reproduction, genetics, and longevity or culling. However, the small number of studies and unclear characterization of what is optimum for reproductive management, other health disorders, economics, and water and energy consumption suggest a need for future research.

Key words: dairy farming, voluntary milking, box robot, robotic milking

INTRODUCTION

Use of automatic milking systems (AMS) is trending upward in the United States, although the adoption rates have been slower than in Europe, where box robot technologies have been used for over 30 years (Baiju, 2020). It has been suggested that the higher proportion of large farms in the US and producer uncertainty about AMS feasibility are the potential reasons for the slower adoption of robotic milking systems compared with European countries (Jacobs and Siegford, 2012). One of the primary obstacles to implementing AMS is the higher costs of milking equipment and facilities compared with conventional milking technology (Salfer et al., 2017). However, trends of future reductions in the availability of labor in the dairy sector, potential increases in labor costs, and improvements in precision dairy farming, milk quality, animal welfare, and environmental sustainability are contributing to the increase in AMS adoption in the US (Cabrera et al., 2020; Cabrera and Fadul-Pacheco, 2021; Cogato et al., 2021).

The US represents a distinct landscape for AMS adoption, with the average number of robots per herd being higher than in selected European countries (2.71 vs. 1.88; Piwczyński et al., 2020a). Indeed, it has been suggested that the implementation of AMS from 2022 to 2030 will be spearheaded by large dairy herds that epitomize the US dairy landscape (Market Research Future, 2022). Most surveys and studies with AMS...
throughout the world indicate improvements in milk production (Jerram et al., 2020), milk composition (De Marchi et al., 2017), milk quality (Castro et al., 2018), cow welfare (Jacobs and Siegford, 2012), mastitis management (Hogeveen et al., 2021), and cow longevity (Mangalis et al., 2020). Several review papers have addressed udder health (Hovinen and Pyörälä, 2011; Litwińczuk et al., 2015; Penry, 2018), management (Jacobs and Siegford, 2012; Varlyakov et al., 2012), welfare (Svennersten-Sjauja and Pettersson, 2008; Jacobs and Siegford, 2012), behavior, and other health disorders (Olechnowicz et al., 2006; Jacobs and Siegford, 2012; Varlyakov et al., 2012). A comprehensive systematic review of scientific and industrial research on AMS over the last 20 years was also recently published, illustrating gaps in future research tendencies (Cogato et al., 2021). However, the geographical nuances of non-pasture-based AMS research focus and potential need in areas such as the US, composed of a significant proportion of large dairy herds, were not underscored.

The premise for the current review is that comprehensive literature analysis can underscore the main challenges and opportunities for future research needed to advance non-pasture-based AMS implementation and sustainability in Europe and other regions, including the emerging interest in AMS in the US dairy sector. The objectives of the current scoping review were to characterize the topics of the research published on AMS in non-pasture-based systems and to provide a critical assessment of opportunities and challenges for future research on AMS on dairy farms worldwide, with a particular focus on the US landscape.

MATERIALS AND METHODS

Protocol and Registration

A scoping review protocol was published in the online University of California repository, available at SYREAF (www.syreaf.org). This manuscript followed the reporting guidelines using the Preferred Reporting Items for Systematic reviews and Meta-analysis Extension for Scoping Reviews (PRISMA-ScR; Tricco et al., 2018). The scoping review followed the methodological framework outlined by Arksey and O’Malley (2005). Because no human or animal subjects were used, this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board.

Eligibility Criteria

Primary research, including descriptive, experimental, and analytical observational studies, was eligible for inclusion in the current scoping review. Eligible articles published in English from any country during or after the year 2000, available in the full text of at least 500 words, were included for further analysis.

Information Sources

Six electronic databases were searched using the PRISMA-S template (based on v1.0, retrieved from https://osf.io/2ybwn/) for potentially eligible studies: Biosis database on Web of Science (1923 to 2022; Clarivate: http://webofscience.com/biosis), CAB Abstracts on CAB Direct (1973 to 2022; CABI: https://www.cabdirect.org/), Medline database on PubMed (1946 to 2022; NIH: https://pubmed.ncbi.nlm.nih.gov/), Scopus (1923 to 2022; Elsevier: https://www.scopus.com/), PubAg (1997 to 2022; USDA: https://pubag.nal.usda.gov/), and Agris (1975 to 2022; FAO: https://agris.fao.org/agris-search/index.do). Gray literature was included by searching S-PAC (Searchable Proceedings of Animal Conferences, 1935 to 2022; American Dairy Science Association: https://spac.adsa.org/index.asp). The Journal of Dairy Science (online; https://www.journalofdairyscience.org/) from 2000 to 2022 was hand-searched by a single reviewer. An updated (bridge) search was conducted across all databases on Aug. 17, 2022, including the years 2021 and 2022. The citations from the database searches (Hermans et al., 2003; Castro et al., 2012; Brzozowski et al., 2018) were uploaded into Zotero 6.0.18 (https://www.zotero.org/) or SciWheel (SAGE Publications; https://www.sciwheel.com) and de-duplicated using internal algorithms. De-duplicated citations were imported into Covidence review management software (https://www.covidence.org/), where additional de-duplication was conducted before eligibility screening. Following the full-text screening, an additional manual de-duplication was conducted.

Literature Search

The literature search was completed on September 16, 2022, using a list of search terms related to AMS. Table 1 shows the entire search string used, which was then formatted appropriately for each database platform used for the current scoping review.

Selection of Sources of Evidence

Two steps of study selection were conducted in Covidence by 2 independent reviewers, comprising questions about the eligibility criteria. The first one was based on the title and abstract, following 4 questions: (1) Is the study with AMS in dairy cattle operations? (2) Is this a primary study? (3) Is this study not exclusively focused on pasture-based AMS? (4) Is the article in English?
Regarding full text, screening followed 4 eligible criteria: (1) Is the study at least 500 words? (2) Is the study entirely in English? (3) Does it describe AMS in dairy cows? (4) Is this a primary study? In both steps, the response selection included “yes,” “no,” or “maybe.” All disagreements were resolved by consensus. Studies focused exclusively on grazing were excluded as being not primarily aligned with AMS used in the US.

Data Charting Process

Data charting was conducted in Covidence by 2 reviewers working independently. The data charting form was pre-tested by all reviewers, and if necessary, modifications were made for question clarity. All disagreements were resolved by consensus. Authors were contacted for clarification or to obtain additional information on eligible studies. If an article described more than one study, the data were charted at the article level (i.e., information from all studies within an article was extracted into a single Covidence form).

Data Items

Study-level data included the year of publication, the year the study was conducted, country of study, study design, study objectives, farm or herd type (research or university dairy, or commercial dairy), breed, the brand of the AMS, housing type, purpose of the study (health; longevity and culling; milk yield, production, and quality; economics; labor; reproduction; nutrition; lameness; and behavior and welfare). When a study encompassed multiple topics, it was included in each relevant category to ensure comprehensive coverage and accurate representation of the overall data.

RESULTS

Selection of Sources of Evidence

Articles related to non-pasture-based AMS published in or after the year 2000 were eligible for inclusion, with the year of publication ranging from January 2000 to September 2022, with 69.4% research papers, 21.1% proceedings, 6.7% abstracts, 1.9% short communications, and 0.9% technical notes. The studies were conducted primarily in Europe (73.5%, 407/554), followed by North America (16.2%, 90/554), Asia (5.2%, 29/554), Australia/Oceania (4.5%, 25/554), South America (0.4%, 2/554), and Africa (0.2%, 1/554). Canada contributed 10.1% of the total AMS studies in North America, while the US contributed 6.1% of the research output. The geographical distribution of the studies varied among the 46 countries, as shown in Figure 2.

Cohort studies, case-control studies, and non-randomized studies were the most common study designs found (26.9%, 24.3%, and 18.7%, respectively), followed by cross-sectional studies (13.2%), randomized controlled trials (9.7%), economic evaluations (2.6%), case reports (2.1%), diagnostic test accuracy studies (0.7%), and systematic reviews (0.4%). Commercial herds were used in 67.9% of the articles (364/536), followed by research or university herds (141/536; 26.3%), and 5.8% were not mentioned (31/536). The primary breeds included were Holstein (57.7%), followed by Jersey (6.7%) and Swedish Red and Swedish Black-and-White (6.7%), crossbred (5.9%), Brown Swiss (5.7%), Holstein-Friesian (3.2%), Simmental (3.0%), and 16 other breeds (11.1%). Cattle breed was not reported in 224 articles. Regarding the AMS brand mentioned in 536 studies, only 34 were derived from publications in the US.
in the studies (443/536), Lely was present in 45.4%, followed by DeLaval (39.7%), GEA (3.4%), Fullwood Packo (2.5%), Galaxy (2.0%), and other brands (7.0%). The AMS brand was not reported in 174 articles.

The type of traffic used in non-pasture-based AMS varied across regions within the studies (Figure 3A, 3B). In Europe and other regions, free flow was the most prevalent cow traffic type, followed by guided traffic.
flow (milk first), guided flow (feed first), and forced flow (Figure 3A). Traffic type was not identified in 364 articles. In contrast, in the US, guided flow (milk first) was slightly higher than free flow, followed by guided flow (feed first) and forced flow (Figure 3B). Traffic type was not identified in 20 articles.

As depicted in Table 2, the study characteristics exhibited similarities between Europe and other regions as well as the US. A small fraction of these studies compared conventional milking systems (CMS) and AMS. In contrast, most studies implemented a strategy involving intervention or exposure (e.g., treatment), irrespective of the region in question.

Over 2 decades (2000 to 2021), the number of studies published on non-pasture-based AMS per year increased, mainly in the last 5 years (Figure 4A), when the US began to contribute effectively (Figure 4B). The research topics investigated in Europe and other regions (n = 524) were milk production, milk composition, AMS efficiency (39.9%), behavior and welfare (14.7%), SCC and mastitis (13.4%), nutrition (7.8%), health disorders (5.3%), economics (4.4%), lameness (2.9%), labor (2.5%), reproduction (2.5%), genetics (2.5%), longevity and culling (1.1%), technology (1.0%), energy consumption (1.0%), water consumption (0.6%), and environment (0.6%; Figure 5A). In the US, studies (n = 37) explored milk production, milk composition, AMS efficiency (62.2%), behavior and welfare (16.2%), mastitis (8.1%), health disorders (5.4%), economics (5.4%), and lameness (2.7%; Figure 5B).

When the study’s time frame was stratified into 4 periods (2000–2005, 2006–2010, 2011–2016, and 2017–2022) for the 6 most common research topics (Figure 6), it was noteworthy that the US contribution to the literature increased between 2017 and 2022 for 4 of 6 topics, but studies on nutrition and health disorders were not conducted in the United States.

**DISCUSSION**

A total of 536 published studies between January 2000 and September 2022 were evaluated to describe the research areas, gaps, and tendencies of the literature on AMS in non-pasture-based dairy cattle operations to target future research. Since AMS was adopted in Europe in 1992 (Bockhahn and Terry, 2022), noticeable increases in the numbers of publications have been observed in specific windows of time in Europe and other regions (2004, 2011–2012, and 2018–2022) and the US (2016–2022). The perceived increase in the number of studies until the mid-2010s is likely explained by the number of farms using AMS worldwide rising from 800

![Figure 3. Traffic type identified in non-pasture-based automatic milking system studies across regions.](image-url)

<table>
<thead>
<tr>
<th>Table 2. Characteristics of studies on non-pasture-based automatic milking systems (AMS) across regions</th>
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<tbody>
<tr>
<td>Study characteristic</td>
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<tr>
<td>CMS(^1) and AMS comparison</td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>No (only AMS)</td>
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<tr>
<td>Strategy of intervention or exposure</td>
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<tr>
<td>Yes</td>
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<td>No (only AMS)</td>
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\(^1\)CMS = conventional milking system.
to 10,000 between 2000 and 2010 (Baiju, 2020). The subsequent increases in the last 5 years are likely linked to AMS technological advancements for precision dairy farming, reduced labor costs, and better lifestyles perceived on dairy farms, despite high initial investment and trade barriers that have made places such as the US lag in the adoption of AMS (Market Research Future, 2022).

The market for milking robots is estimated to be worth US$2.4 billion in 2022 and is projected to reach US$4.2 billion by 2027, at a growth rate of 11.7% during the forecast period (Research and Markets, 2022). Therefore, identifying understudied areas or areas flagged as challenges for AMS is pivotal to shedding light on topics that researchers need to invest in to support AMS dairies’ sustainability. Most studies were conducted in Europe and Canada, because these were the pioneer countries adopting this technology, and focused on topics that represent areas such as milk production and AMS efficiency that could explain and justify the viability of robotic dairies (Świtłyk et al., 2019; Padua et al., 2021). However, as shown by our findings, studies published in the US have increased in the last 5 years. In a survey conducted by our group on dairies with ≥7 AMS in the US, adoption is trending higher mainly to improve cow welfare and herd performance and reduce labor costs and numbers of employees (Lage et al., 2021). Growing awareness of the benefits of AMS and advanced data availability for precision dairy farming, especially in large herds and mobile applications, are significant factors contributing to the increase in market opportunities (Research and Markets, 2022).

In the first 10 years analyzed in the current scoping review, the primary research interest was understanding how AMS works regarding milk production and composition, followed by behavior and welfare, mastitis, and SCC. Milk yield and composition continue to be the central areas of interest for researchers, and the focus has shifted in the last 10 years to improving AMS efficiency and helping herd management. The data on milk composition suggest that lactose and urea have increased while fat content and dry matter were lower due to higher milk yield in the AMS system (Kolenda et al., 2021). These small changes in milk composition did not influence efficiency of the cheesemaking process, cheese composition, or cheese sensory profiles. Milk harvested with AMS has normal proteolysis and does not appear to modify the distinctive characteristics of cheeses (Innocente and Biasutti, 2013; Franceschi et al., 2022). Recent studies have looked at selecting cows for milking speed, teat attachment, and identifying disorders before they become severe, preventing consequences that could influence cow longevity.

Increasing milk frequency and milk yield, improving behavior and welfare, and detection of mastitis have been the consensus in most studies when herd management was adjusted to fit the AMS in non-pasture-based system. Studies showed that the use of AMS may affect SCC levels, mastitis incidence, and teat conditions (Vliegher et al., 2003; Suzuki et al., 2022). However, the udder health effects of transitioning from CMS to AMS can be less severe to negligible when initial cow health status and management are adequate (Frössling et al., 2017; Kurokawa et al., 2021; van den Borne et al., 2021). The results of this field trial confirm that AMS have no negative effects on IMI incidence, SCC, and teat tissue conditions. It is noteworthy that, to achieve this advantage, it is necessary to be attentive to accurate detection of the teat position, attachment of milking cups, incomplete milkings, proportion of cows...
having a new elevated SCC, as well as selection of cows for AMS based on behavior and udder conformation (Nogalski et al., 2011).

From an animal welfare perspective, free-cow traffic has been considered a better option because cows might spend more time in resting areas and cubicles than in guided flow (Forsberg, 2008; Lexer et al., 2009). Studies about the effects of free flow and guided flow on disease and culling are also areas for further research opportunities. After 2016, increased interest in nutrition, health, reproduction, longevity, and environmental aspects has been noticeable. The increased interest in nutrition stems from the fact that the AMS system offers an opportunity to feed cows individually when visiting the robotic unit and to direct the use of pellets and supplements to match cows’ nutrient requirements more precisely (Hare et al., 2018; Haisan and Oba, 2020; Johnson et al., 2022). Considering the diverse availability of feed sources and various nutritional management in places such as Europe and Canada compared with the US, it is reasonable to surmise that specific geographical location studies will be needed to optimize the feeding system in AMS dairies in the US.

The opportunity to integrate the wealth of sensor data generated by AMS toward the early detection of cows at high risk of developing health issues is tantaliz-
ing (King et al., 2017a,b). Studies in Europe and other regions have explored biomarkers from AMS as earlier indicators for mastitis, lameness, subclinical acidosis and ketosis, and hypocalcemia (Antanaitis et al., 2019; Bonestroo et al., 2021; Televičius et al., 2021). However, studies focusing on metritis are lacking, and hitherto no studies on disease biomarkers have been conducted in the US. Mathematical models using statistical inferences and machine learning models, as previously shown in CMS dairies (de Oliveira et al., 2021), integrating disease biomarkers data with animal behavior data for early diagnosis of health disorders, are a potential area to be explored further in AMS dairies.

Lameness negatively affects milk production, voluntary milking behavior, and lying behavior of cows in AMS herds (Westin et al., 2016; Bugueiro et al., 2019; Villettaz Robichaud et al., 2019) and is influenced by environment, genetics, and bedding. Due to this, it is essential to optimize herd-level productivity in AMS by using adequate materials for bedding, managing stocking density and curb height of the lying stalls, ensuring adequate feed access and feed bunk space, and maintaining proper cow body condition (King et al., 2016; Matson et al., 2022).

Most studies showed that herds transitioning from CMS exhibited positive influences on days open, number of services per conception, and age at first calving (Brzozowski et al., 2018; Piwczyński et al., 2020b). The use of automated activity monitoring in AMS dairies aids in estrus detection. Still, it is pivotal to underscore that the average anovulation rate postpartum in large dairy herds in the US, around 60 d in milk for dairy cows, ranges from 23.3% to 41.7% (Bamber et al., 2009). Therefore, relying upon estrus detection on large herds with high-producing dairy cows may have a detrimental influence on overall reproductive performance, and it should be an area of focus for future research.

Management strategies such as Presynch, Ovsynch, and Double-Ovsynch are already known for reducing the percentage of anovulatory cows and increasing

Figure 6. Number of studies by most prevalent areas of interest, conducted in Europe and other regions and the United States, related to non-pasture-based automatic milking systems.
conception at the first service (Moreira et al., 2001; Souza et al., 2008). Although recent studies have indicated that selection based on the genomic prediction of daughter pregnancy rate could be integrated to improve overall performance (Lima et al., 2020) with benefits toward the expression of estrus (Veronese et al., 2019), that effect is unknown on AMS dairies and deserve further investigation. Strategies such as using GnRH (Burnett et al., 2022; Hubner et al., 2022) in cows detected estrus also deserves further research to optimize reproductive outcomes in AMS dairies.

Cow longevity is based on genetic gain, health care, reproductive performance, and indirect animal welfare factors (De Vries, 2020). Improvements in animal welfare have been observed in AMS; cows in AMS have more freedom to control their daily activities and rhythms than in CMS (Jacobs and Siegford, 2012). A study conducted in Spain showed that the risk of loss due to death or emergency slaughter decreased when switching from CMS to AMS (Bugueiro et al., 2019). These findings suggest that AMS may improve the cow life span, which can help increase profitability. Assessment of similar outcomes in larger AMS herds, representing the US landscape, can help validate the potential value of AMS implementation.

Sustainability in dairy production includes environmental, economic, and social dimensions of sustainable development (Segerkvist et al., 2020). Farmers implementing AMS also look for labor and energy savings, water consumption, and gas emission benefits. According to studies, AMS can decrease labor time and the number of employees required (Steeneveld et al., 2012; Drach et al., 2017; Tse et al., 2018). A rigorous assessment of labor costs and cost-benefit of AMS implementation that represents various scenarios depicting the current spectrum of AMS dairies in Europe and other regions and the US landscape still needs to be investigated.

Electric consumption is one of the most relevant operational costs of AMS, ranging between 35 and 40% of their total annual operational costs. It is mainly conditioned by farm management rather than machine characteristics (Calcante et al., 2016). Considering the efficient use of energy and renewable energy sources, energy saving is possible in AMS, but a gap in the literature still exists. Only 3 studies were found regarding water consumption, but none compared the water use between AMS and CMS. According to Krauß et al. (2016), AMS water used in the barn contributes only to water use in dairy farming compared with water used for feed production. The average amount of water consumed by AMS per 1 L of milked milk was 0.33 L and is influenced by multiple factors, including performance, animal health, and current climatic conditions (Vaculík et al., 2021). Optimizing the use of all AMS subcomponents and regularly monitoring energy and water consumption by meters installed on equipment has been suggested as a strategy to achieve better AMS efficiency (Rasmussen, 2005). Further research is needed to elucidate whether AMS in non-pasture systems significantly reduces energy and water consumption compared with CMS.

The economic impact of AMS technology is a major deciding factor for farmers to adopt it. Most of the studies evaluated AMS economic impact using simulation models from surveys. In one of the studies, AMS had increases of 8.66% for milk yield, 58.46% greater investment costs, 36.66% increase in energy consumption, 1.33% increase in feed costs, and a decrease of 27.84% in labor input compared with CMS, but herd size can affect the profitability (Örs et al., 2022). Changes in milking labor costs and milk production were major management factors influencing the net annual impact (Salfer et al., 2017). Although the production-related expenses are higher on AMS farms, the gains are visible after a transitional period of approximately 4 years (Hansen et al., 2019). As a result, knowledge of the areas that influence AMS profitability is essential for future research, and further investigation is needed, focused on implementing AMS in large herds representing the current US trend.

**CONCLUSIONS**

This scoping review of AMS research topics worldwide over the last 20 years underscored gaps in US studies compared with Europe and other regions, revealing future research needs. In the last 5 years, there has been increased global research interest in energy and water consumption, technological development, environmental effects (enteric emissions), reproduction, genetics, and longevity and culling. In the United States, research and implementation of AMS are growing steadily, and, in addition to the global tendencies, studies on nutrition are lacking, suggesting that to improve AMS efficiency in the future, studies that critically investigate those areas need to be further considered.

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