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REVIEW

Innovation, practical benefits and prospects for the future development of automatic milking systems

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Abstract Automatic milking systems (AMS) were designed to replace existing, labor-intensive machine milking and are an area of rapid development in modern dairy farming. The popularity of AMS lies in the convenience of management, decreasing workloads and the consistency of milking compared with non-automated machine milking. Nevertheless, this innovation has not been reviewed comprehensively and the practical benefits of AMS are still unclear. This review gives a brief overview of the historical development of milking machines and the workflow process of state-of-the-art AMS. In addition, a series of comparisons between AMS and current milking machines are made with respect to labor savings, quality parameters, udder health, herd behavior and mastitis detection and are summarized on the basis of relevant studies to show the benefits of the technological changes achieved by AMS. Finally, this review addresses several deficiencies in the technology and procedures of current AMS that need to be improved and also assesses recent advances in milking techniques with a particular focus on their potential for application in AMS.

Keywords automatic milking systems (AMS), innovation, milking machine, practical effect, future prospects

1 Introduction

Cow milking, including barn sanitation, teat treatment, mastitis prediction and checks of udder condition and milk quality, is complex and onerous. Historically, cows were all milked by hand and a previous study indicated that 40% of the dairy workers had problems with their back and 30% with neck and shoulder injuries[1]. In response to the magnitude and expense of labor in dairy practices, the development of milking machines globally has undergone a revolution in technological innovation since the 19th century[2]. Initially, milking machines underwent incremental innovations as a series of experimental prototypes were developed to explore the applicable technology, while after the validation of this process, further technological innovation evolved into the modern systems[3]. From the 1970s it became clear that the needs of the dairy industry were not being met by the available milking technology, and much research has been undertaken in developing methods to alleviate the workflow bottlenecks and constraints in time management in dairy farming practice.

Unmanned and automated systems became the focus for the advances in dairy farming. Consequently, automatic milking systems (AMS) were deemed essential for improving working conditions, increasing time availability and saving on labor costs. The earliest AMS appeared in the Netherlands in 1992[4–6], and represents one of the most significant technological advances in the dairy industry due to its capability to reduce negative human influences, such as procedural error and microbiological contamination on the resulting milk quality. After the introduction of the first AMS, the adoption of the new technological innovation proceeded slowly and in 1996 only about 45 installations were used on commercial farms with the majority in the Netherlands[7]. By the end of 2009, AMS was estimated to be deployed on more than 8000 dairy farms in over 25 countries worldwide[8] and the number rose to 10000 by 2010[9,10]. Today, the number has risen to 30000, not only in European countries, but also in Japan and North America[11,12]. Unquestionably, AMS has become an accepted technology in the modern dairy industry and is gradually becoming mainstream practice.

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Currently, different AMS realize the automation of milking, even including the entry and exit of cows. This not only saves labor, but also generates an overall upgrading of milk yield, milking frequency, milk quality, udder health and animal welfare. Along with the increasing adoption of AMS technology, a number of studies have reported an analysis of social and economic effects of labor savings and improvements in milk, quality and yield. A summary of the comparison of research results for AMS and non-automated machine milking is necessary to determine the superiority of AMS. This comparison would also help to identify deficiencies of current AMS and contribute to identifying areas for future development and innovation.

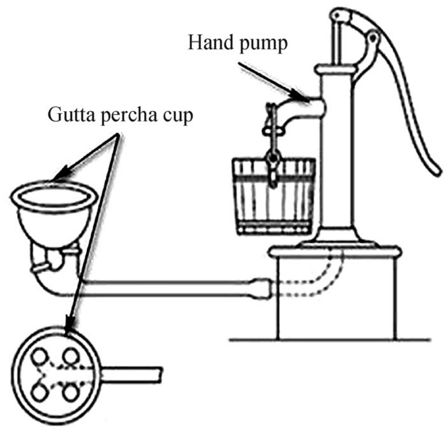

Fig. 2 The earliest vacuum milking machine, circa 1851[14]

2 The development of milking machines

2.1 Non-automated milking machines

The first appearance of milking machines dates back to 1819, when machine tubes made of wood or featuring quills, which could be inserted into the teats, forcing the sphincter muscle to open and allowing milk to flow out of the mammary gland[3]. The materials used in these so-called catheter milking machines[13] (Fig. 1) then progressed to silver, ivory or bone, and they were in use until the 20th century. To avoid problems caused by catheter milking, such as disease spread through microbial cross-contamination, continuous leakage from weakened sphincter muscles and injury to teats, the earliest vacuum machine was developed (Fig. 2). This innovation was made by Hodges and Brockenden in 1851 and used a large gutta percha cup connected with a hand pump, which was operated by fitting over the entire udder[14]. The vacuum machine was tested empirically and was successful commercially when introduced to the British market in 1889. This kind of milking machine was known as the Murchland milking machine after its inventor William Murchland (Fig. 3), and used a vacuum instead of pressure developed by mechanically squeezing teats[15].

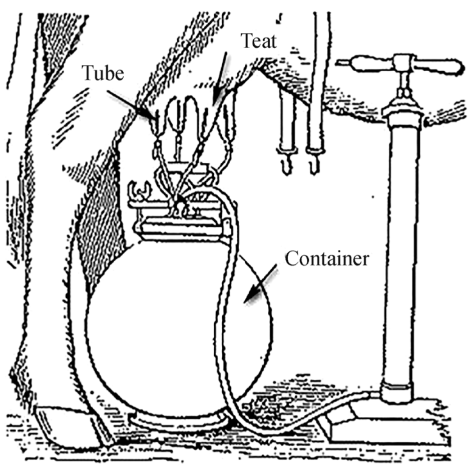

Fig. 1 Catheter milking machine, circa 1819[13]

Since then, pulsation, which was achieved by a hand-pump or foot-pump design, was considered by inventors to further improve milking efficiency. In 1898, the famous Thistle machine was the first to incorporate such a pulsator into the design, which combined a steam-driven pump to effect both suction and squeezing movements[16]. This key development and the recognition of the utility of pulsation contributed to it becoming and remaining one of the main components of milking technology to the present day. So, the basic components of a modern machine are a vacuum system and pulsation, as a means of transportation and collection of milk, both of which can be traced back to these early machines[3].

Along with the increase in intensive farming practices, the demands for milking of dairy cows on a large-scale also arose. Milking parlors have been in development to address this problem since the 1930s, but only after the invention of the herringbone milk parlor in New Zealand in 1952 did the number increased rapidly[17]. Since then two types of milking parlors have been used, static and rotary parlors with the best-known types of the static configuration being the side-opening (tandem), herringbone and the parallel parlor (Fig. 4a)[18] In static parlors, milking units are located side by side against a pit, and this design enables an open platform exit which is ideal for larger breeds and pregnant cows. In operation, dairy workers would move around the milking parlor from stall to stall while in the rotary parlors (Fig. 4b) the workers do not have to walk as much, which is a benefit of the rotating platform. Also, in the rotary parlor, the cows do not have to move backward over a large distance, which allows for a swift entry and a higher throughput of animals.

The constraints imposed by milking machines, such as the need to herd cows into parlors and the intrinsically

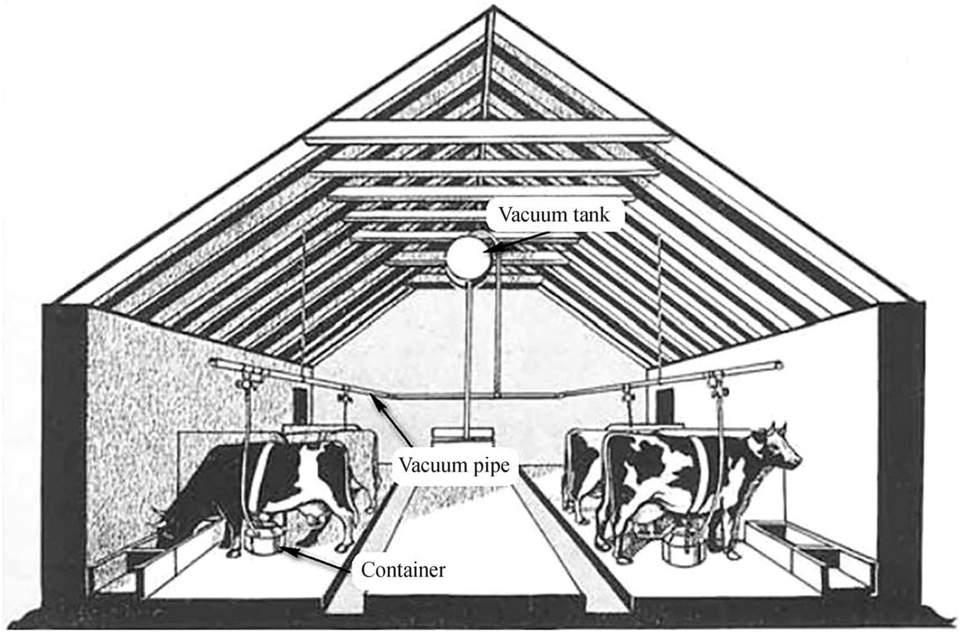

Fig. 3 Murchland milking machine, circa 1889[15]

(a)

(b)

Fig. 4 Two different types of milking parlors. (a) Parallel milking parlor (Midiline, DeLaval, Sweden)[19]; (b) rotary milking parlor (HBR, DeLaval, Sweden)[20].

longer time involved, this spurred the search for innovations to seek new approaches to circumvent these procedural obstacles and alleviate bottlenecks in the workflow. In the late 20th century, the development of AMS represents one of the most significant technological advances in the dairy industry since the introduction of machine milking.

2.2 Automatic milking systems (AMS)

AMS refer to systems that automate all stages of the milking process and cow management undertaken in non-automated milking systems[4]. AMS utilize a robotic arm to attach and detach the teat cups to the udder without human intervention and can result in a significant reduction (20%–30%) in total farm labor-hours[12]. Thus, automatic milking is also referred to as robotic milking. To date, three main types of AMS have been developed and these exemplify the current advanced-level of the technology worldwide: integrated AMS, industrial robotic AMS and the automatic milking rotary system.

2.2.1 Integrated AMS

Integrated AMS represents the most widely used configuration and several companies supply products of this type. The equipment supplied by Astronaut (Lely, the Netherlands), VMS (DeLaval, Sweden), Merlin (Fullwood, England), Mlone (GEA, Germany) and MR (Boumatic, USA) all belong in this class, among which the Dutch Astronaut integrated AMS is a notable representative. These integrated AMS type machines

(Fig. 5) have a milking area to receive cows to be milked. The robotic arm is initially stored in a position adjacent to this milking area and moves outward when activated to locate the teats and to attach the teat[21]. This AMS operation requires a number of steps from cow entry to exit.

Fig. 5 Integrated automatic milking systems (Astronaut, Lely, the Netherlands)[22]

(1) Cow entry

The AMS comprises an entry gate allowing cows to enter the milking area. If an animal is willing to be milked and voluntarily moves to the AMS, the gate will sense the ID of the cow and then let it in.

(2) Feed and teat preparation

After entry, the feeding system feeds the cow in order to calm the animal during the procedure. The entrance gate automatically registers the ID tag (transponder) which stores individual teat positions for the robotic arm to track. The robotic arm locates the teats by ultrasound, laser or image analysis[23] to identify the exact position for attachment. Then, each teat is cleaned in turn with water by a special teat cup and teats are dried after cleaning. While the cleaning and drying procedure is taking place, a small amount of foremilk is released into the wash water. Other cleaning techniques, such as most notably brush cleaning, are also used by integrated AMS.

(3) Milking cup attachment and automatic cluster removal

The robotic arm picks up one or more teat cups at a time and attaches them to the teats employing either a laser camera or other techniques to locate the exact position, which typically takes about 12 s to complete[18]. Milking starts as soon as the milking cups are on the teats, and it is monitored per teat by sensing systems for measuring flow, yield and conductivity among other parameters. If the milk flow is interrupted, the cup will be individually removed from the teats and retracted into the original positions.

(4) Teat spray and cow exit

Spraying of teats with disinfectant can also be performed by the robotic arm when milking is complete. After spraying, the exit gate opens to let the animal out. Between exit and the next entry, the milking cups will be rinsed inside and out with water for sanitation.

2.2.2 Industrial robot AMS

Industrial robot AMS uses a fully developed industrial robotic arm to attach milking cups, which are located separately adjacent to the milking box. Globally, companies manufacturing this AMS configuration, include ProFlex (Boumatic, USA), Futureline MARK II (SAC, Denmark) and Galaxy Starline (Insentec, the Netherlands) among which the ProFlex (Fig. 6) is the most well-known. The essential characteristic of this AMS is that the industrial robotic arm is a proven technology and one single robotic arm can serve two cows when set up side by side as a double-box configuration, which significantly reduces the overall costs of milk production. Although the milking arm is separated from the box, overall the workflow process is similar to the integrated AMS type.

Fig. 6 Industrial robot automatic milking systems (ProFlex, Boumatic, USA)[24]

2.2.3 Automatic milking rotary system

Based on the design of rotary milking parlors, the automatic milking rotary system of AMR (DeLaval, Sweden) was released in 2010, and is comparable to the configuration and workflow of the DairyProQ (GAE, Germany). A double saloon gate secures one cow at a time stepping onto the platform, and then the platform rotates to the next stop position for teat preparation so that the next cow can enter the platform. This system generally possesses five robots, two for teat preparation, two for milking cup attachment (Fig. 7) and one for spraying disinfection after milking. In other words, four robots would serve four cows at the same time, which greatly improves the efficiency of the procedure.

3 Advantages of AMS in comparison with non-automated milking

AMS is particularly advantageous in reducing the influence of human factors, which is the principal trend in the automation of the dairy industry. The demands of

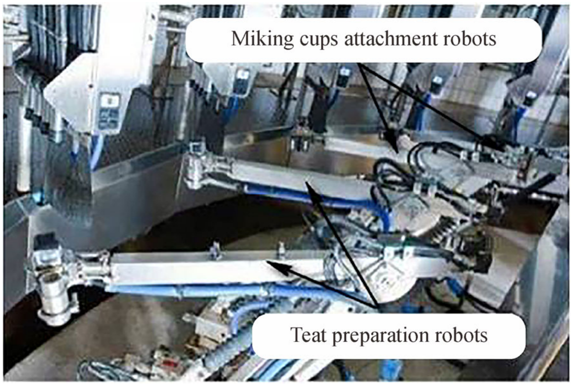

Fig. 7 Teat preparation robots and milking cup attachment robots (AMR, DeLaval, Sweden)[25]

improving conditions for dairy workers, increasing time availability and saving labor costs led directly to the necessity to develop AMS. Robotic milking systems meet most of the natural needs of the cows, and because cows are free to choose their milking time the waiting time before milking is reduced[26].

The primary difference between non-automated machine milking and AMS is that AMS does not require a person to be present when cows are milked[27]. In addition, the other main advantages of AMS are discussed below.

3.1 Labor savings

Before AMS technology became widespread, about half of the labor expense for large dairy herds was related to milking. Dairy farmers reported that morning milking, afternoon milking and parlor maintenance took more than 4 h per day[28]. Therefore, AMS significantly improves the efficiency of labor by milking parlor equipment such as automatic cluster removal, and rapid entry and exit gates[29]. By using AMS, farmers are freed from the milking process and the associated rigid schedule, and labor can be devoted to supervision of animals, feeding and other activities.

A number of studies[30,31] have shown that improvements in quality of life and the reduced time spent on milking were the primary benefits realized by the introduction of AMS. Additional research results for labor reduction together with milking frequency and yield for different methodologies in different countries are presented in Table 1.

It can be readily seen in Table 1 that following adoption of AMS technology, labor savings are significant (20%–50%), which is the major reason that dairy farmers around the world adopt AMS. The data also show that milk frequency and yield generally increase with AMS, which may result from the lower stress on the udder and the increased comfort for the cows. However, the frequency and yield of milking may vary, which is mostly attributable to the influence of the farming environment, animal health and climate.

3.2 Milk quality

Milk quality is an issue of public concern, especially in the change to AMS. This comprises hygienic quality and nutritional composition, with the important parameters being somatic cell count (SCC), total bacterial count (TBC), freezing point, anaerobic spores, free fatty acids (FFA), and the content of fat, protein, lactose, casein and urea.

A study by Ipema[39] reported that SCC was low for the robotically milked cows in a Dutch trial. Pomiès and Bony[40] concluded that AMS did not substantially change the hygienic quality of milk as determined by French milk payment criteria. Berglund and coworkers[41] found that milk quality in the AMS was comparable to non-automated milking and in some cases was superior. Also, Wirtz and colleagues[42] showed that fat content was 0.23% lower in cows milked by AMS but no differences in protein content were detected. Additionally, with the more widespread adoption of AMS technology, a number of studies have been published on changes in milk quality. Table 2 presents a comparison of the quality of milk produced by AMS and non-automated milking machines.

There is no statistically significant evidence for an overall quality effect of AMS. Differences may relate to the different study sizes, designs, processes and conditions, for

Table 1 Changes in milking frequency, yield and labor by automatic milking compared with non-automated milking

Region	Labor reduction	Milking frequency	Yield increase	Method/Scale	Reference
The Netherlands	30%–40%	–	–	Model study	[32]
France	–	–	3% (< 2 years), 9% (> 2 years)	44 large farms	[33]
European countries	19.8%–21.3%	–	–	Questionnaires	[34]
The Netherlands	29%	–	Basically the same	62 farms	[35]
Denmark	50%	2.7 (summer), 2.4 (winter)	Above 19%	9 AMS and 9 non-AMS	[36]
Finland	30%	–	Not higher	Varied from Con to AMS	[37]
Poland	–	2.5–3.0 times	Above 12%	Farm of 50 cows	[38]

Note: –, not given; European countries, includes Belgium, Denmark, Germany and the Netherlands; non-AMS, farms using non-automated systems.

Table 2 Comparison of milk quality parameters between automatic milking and non-automated milking machines

Region	SCC	TBC	Freezing point	Anaerobic spores	FFA	Fat content	Protein content	Reference
The Netherlands	Higher	Higher	Higher	–	Higher	–	–	[43]
Israel	Clearly lower	–	–	–	Lower	–	No difference	[44]
Denmark	Higher	Higher	0.007°C higher	–	–	–	–	[45]
The Netherlands	A bit higher	A bit higher	A bit higher	–	A bit higher	–	–	[46]
European countries	A bit higher	A bit higher	A bit higher	–	A bit higher	–	–	[47]
Finland	Higher	Higher	Clearly higher	No difference	Higher	Higher	–	[48]
America	No difference	Lower	–	–	–	–	–	[49]
Denmark	No difference	–	–	No difference	Higher	No difference	No difference	[36]
Poland	Lower	–	–	–	–	–	–	[38]
Latvia	Clearly lower	–	–	–	–	Lower	Lower	[50]
Czech	Clearly lower	Higher	Clearly lower	–	–	Clearly higher	Clearly higher	[51]

Note: SCC, somatic cell count; TBC, total bacterial count; FFA, free fatty acids; –, not given; European countries, include Germany, Denmark and the Netherlands.

example, in different countries, farms, dairy breeds and even the brands of AMS. Additional potential contributory factors may include for example, animals being in different stages of lactation and reproductive cycles, which could also influence the values of the main parameters of the milk quality studied. Potentially, the most significance factor may derive from the fact that there is no daily limit on the number of milking times when using AMS. Non-automated machines are used at fixed times (i.e., twice a day), while the nature of AMS is non-fixed. However, the continuous use of milking lines which reduce the time window for cleaning, and the constant addition of milk to the bulk milk tank, which may not be sufficiently cooled to a sufficiently low temperature, may lead to quality changes and deterioration in milk quality. Therefore, more adequately controlled studies taking into account some of these potential confounding factors need to be undertaken. Guaranteeing the time for cleaning of teats and cooling of milk seems to be particularly necessary with respect to TBC, FFA and freezing point as these parameters generally increase for AMS (Table 2). Despite these slight changes, there are no major concerns about milk quality with respect to nutritional and microbiological standards, which is likely to be due to the pulsation milking principle of both AMS and non-automated milking operations.

3.3 Udder health

Besides labor, milk yield and milk quality, improvements in animal health and welfare are also considered likely outcomes of more widespread adoption of AMS by the dairy industry. After the introduction of AMS, cows are milked more frequently, which leaves less time for bacteria to develop in the udder between milkings. However, teat canals are also opened more often with the more frequent milking, which may cause a higher risk of bacterial invasions[52,53].

Mastitis is an inflammation of the mammary gland caused by bacterial infections, and its detection is important in ensuring udder health. Clinical mastitis can be easily detected, while subclinical mastitis is not so easily discerned and requires a diagnostic test for detection, which is indicated by a mid-range SCC when clinical mastitis is present. In the majority of published studies, udder health deteriorated after the introduction of AMS with a higher average milk SCC[54–62]. Other studies indicated that there was no significant difference in udder health compared with non-automated machines by measuring mastitis incidence or SCC[41,42,63]. In contrast, Lopez-Benavides et al.[64] reported a higher incidence of clinical mastitis occurring with non-automated machine milking compared to AMS, which showed that udder health was positively affected by a change to AMS.

Bennedsgaard et al.[65] reported an increase in antibiotic treatments for mastitis in 20 farms after the introduction of AMS. The alert frequency following adoption of AMS increased; however, not all would have needed treatment. This phenomenon completely relies on the non-automated detection in AMS, and this needs a further refinement to ensure confidence. Also, high milking frequency in improper lactations may also give rise to this scenario and should be adapted individually for cows according to their state of lactations. The conclusion from existing research appears to suggest that udder health slightly deteriorates after the introduction of AMS.

3.4 Animal welfare

Animal welfare involves multiple parameters, such as health, productivity, stress hormone levels, behavior and preference indicators[66]. Although many factors affect the welfare of dairy cows on a farm, cows milked by AMS can manage their daily activities with more freedom and have more opportunities to interact with their environment[67].

Several researchers have compared the behavioral and physiological stress responses of cows during milking in AMS with the cows in non-automated farms, showing the heart rate of cows in AMS were similar to or lower than those observed in non-automated farms[68–71].

Lameness is one of the biggest welfare and economic issues in modern dairy production, which may decrease milk yield from 4 months prior to and for 5 months after the cow is diagnosed as clinically lame[72]. The incidence of lameness in the USA is reported as 15% of the adult dairy cow population[73], and it has been suggested that farmers fail to recognize 75% of the cases[74]. Rajkondawar et al.[75] developed a mathematical scoring system for lameness to detect lameness in individual limbs in AMS. Furthermore, research on cow body mass[76,77], combining breath sampling, existing herd management records, daily milk yields, measurement of ketones and urea[78] were conducted to detect cow health in AMS. Increased movement (step and kick behavior) is considered to be a sign of agitation and has been used to assess cow comfort during milking[67,79]. In response to these findings, several studies were conducted on AMS and these showed no differences or less stepping and kicking in AMS[69,80–82], but one indicated an opposite result with more stepping and kicking in AMS[79].

Other research relating to medical science showed there were lower maximum plasma adrenaline and noradrenaline concentrations in the cows milked by AMS compared to the cows milked by non-automated machines and indicated that cows experienced less stress in AMS[68]. Moreover, levels of milk cortisol and fecal corticosteroids did not differ between cows milked by AMS and those on non-automated farms[70,83,84].

In summary, the evidence suggests AMS reduces physiological stress and discomfort compared with non-automated milking to a certain extent, and AMS is also able to monitor and detect cattle health and behavior. Nevertheless, further research is needed due to the conflicting and contradictory results reported to date.

4 Current deficiencies and future prospects for further development of AMS

AMS represents a major technological innovation in the dairy industry. However, there are still a number of important deficiencies that require addressing. For example, pasture-based cows must be trained to approach the milking unit in response to acoustic signals during the grazing season.

AMS undoubtedly performs well in saving labor. Nevertheless, most farmers indicate that some effort is still required for herding cows, which remains the biggest factor preventing producers from realizing anticipated labor savings[67,85]. Borderas et al.[86] indicated that cows which need to be herded to the AMS may have problems with mobility or lameness. In line with this research, detecting lameness automatically in AMS is clearly necessary. However, other reasons are likely to exist, and experiment should be conducted in rewarding cows with much more palatable concentrates. Another possible explanation of this phenomenon may be related to the fear of operators, which needs further confirmation in studies. It is likely that additional remote control functions devised for AMS may be helpful in the future, such as Bluetooth or infrared communication technology.

In terms of milk quality, FFA of milk is higher in AMS than in non-automated milking, which is considered to result from the shorter milking intervals[87]. Similarly, freezing point generally increases due to the higher water content of milk collected by AMS, which is also ultimately due to the shorter milking intervals. Hence, adapting novel AMS functions to achieve optimal milking intervals should be explored. It is worth noting that substantial quantities of quality and health data need to be collected to determine the best time of day and milking frequency for each dairy breed in different lactation and reproductive cycles.

For mastitis detection, current automated detection methods are performed using electrical conductivity (EC), SCC instruments or color detection, and EC is the most commonly used automated test in AMS. However, for mastitis detection, EC is not reliable and the predictive accuracy is not yet sufficiently high[88]. Kawasaki et al.[89] have indicated that near-infrared spectroscopic (NIRS) sensing systems are able to assess SCC in milk and other milk quality parameters. Correlation coefficients of the above research are high, which indicates that NIRS has potential for diagnose of mastitis and other diseases. In research comparing electrical impedance (EI) with EC detection in milk by Bertemes-Filho et al.[88], EI was better for detecting parameters associated with milk quality, and the authors predicted that the result would be similar for mastitis diagnosis. Cui et al.[90] established a neural network predicting model for EC, temperature, pH and capacitance, in which the detection rate for mastitis is theoretically 100%. The new techniques have the potential to detect mastitis as well as or better than EC, but in-depth research is needed to confirm the feasibility of improving mastitis detection in AMS. In summary, the future focus of research should be to investigate how to improve the predictive and diagnostic accuracy so that AMS can become smart systems enabling real-time monitoring of animal health, milk quality and diagnosis of disease.

Although AMS shows positive characteristics with respect to animal welfare, further studies are needed to evaluate how many stations of AMS would optimally serve particular herd sizes and breeds. Modeling to optimize of cow traffic in AMS could help provide the most efficient service and reduce the incidence of lameness. In addition, such a model could ensure that teat cleaning and milk cooling time do not cause decreases in milk quality though operational overload or suboptimal resource allocation. In particular, a comparison of different AMS manufacturing characteristics has not been undertaken to date, and such a comparison could assist farmers to choose the best model and encourage improvements in commercial AMS technology.

Most importantly, the cost of AMS is a significant barrier to adoption. The high price requires farmers to invest significant funds in capital and subsequent maintenance. Running costs are also affected; electricity consumption is increased whereas water and chemical consumption is nearly halved. Financial benefits were poor during the 10–15 years after adoption of AMS, which is similar to in cost-benefit analyses for non-automated milking systems. Therefore, it is important to find innovative technological approaches to reduce costs and enhance benefits in the future.

5 Conclusions

AMS, which was developed for non-automated machines invented nearly two centuries ago, has been widely adopted in Europe and America over the last two decades. Compared with non-automated systems, studies showed that AMS has certain advantages in labor efficiency, milk frequency, milk yield and animal welfare. However, AMS has unsolved deficiencies including slight reductions in milk quality and udder health. In general, milk FFA and freezing points increase due to the shorter milking intervals, and TBC also increases due to the shortened cleaning and cooling time. Also, the current mastitis automated detection is not reliable. To improve the capacity of AMS in milking, a new mastitis detection method must be developed using improved monitoring technology.

Determining the best milking interval for each dairy breed and cows in different stages of lactation and reproductive cycles may be an approach to solving the problem of quality deterioration associated with adoption of AMS. Determining the optimal number of AMS stations to most efficiently serve different herd sizes should be considered due to bottlenecks associated with herding cows and because quality parameters (TBC, FFA and freezing point) increase with the overloading of AMS operation.

In summary, AMS is an advantageous technology which possesses a number of key advantages over non-automated milking although deficiencies still exist which need to be resolved through further technological innovations. Further research is also needed to improve AMS capacity, reduce costs, increase benefits and ultimately to enable more widespread usage.

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Compliance with ethics guidelines Hongzhe Jiang, Wei Wang, Chunyang Li, and Wei Wang declare that they have no conflict of interest or financial conflicts to disclose.

All applicable institutional and national guidelines for the care and use of animals were followed.

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