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Review

Virtual Fencing Technology for Cattle Management in the Pasture Feeding System—A Review

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Abstract: Maximizing annual pasture consumption without negatively impacting individual cow performance is of great importance in grass-based dairy and beef systems due to pasture being the most cost-effective nutrient source. However, the disadvantages of conventional and electric fencing include material and labor costs and increased manual labor. Virtual fencing has been developed and evaluated for almost two decades. The evolution of precision livestock farming, specifically virtual fencing, presents new opportunities for maximizing the utilization of available pasture land. Virtual fencing technology decreases the labor involved in physical fencing, provides greater adaptability to changes in pasture conditions, increases precision and efficiency, and offers additional flexibility in grazing management practices. However, that innovative technology should be further developed, and improvements should include decreasing the total costs of the system and increasing its application to other technological groups of ruminants, e.g., suckler cows with calves, increasing the efficiency of the system operation in large areas and a larger number of animals. Recent advancements in electronic communication and device (i.e., collar) design hold the potential to significantly enhance the effectiveness of the technology while also reducing costs. However, it is necessary to conduct a further evaluation to determine their utility in precision agricultural systems. This review paper aims to present an innovative concept of virtual fencing technology for pastures, compare currently available systems of this type, and indicate areas where further research and development should be carried out using Internet of Things (IoT) systems.

Keywords: cattle; grazing; herd management; pasture; virtual fencing technology

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1. Introduction

Grasslands represent one of the largest vegetation types on Earth. They are used mainly as pastures and are the predominant forage source for grazing animals [1,2]. Maximizing annual pasture consumption (t DM/ha) without negatively impacting individual cow well-being is of great importance in a pasture-based dairy system due to grazing pasture being the most cost-effective nutrient source [3,4]. Moreover, beef production systems typically include pasture-based cow-calf and stocker-backgrounding or grow-out systems [5]. However, the basis for obtaining high-quality forage from pastures is their rational use, which includes, among other things, rotational grazing with appropriate rotation length, appropriate fertilization with nitrogen and macronutrients (including calcium and magnesium fertilizers), pasture topping, reseeding with valuable species of grasses and legume plants, elimination of weeds, removal of molehills, spring and autumn maintenance, and regulation of soil hydrological conditions. A well-maintained pasture provides grazing animals with high-quality roughage, containing mainly energy, protein, macro- and microelements, and vitamins [4,6,7]. In addition to valuable species of grasses and legume plants, the composition of the pasture sward includes herbs containing several biologically active substances (tannins, saponins, terpenes, flavonoids, pectins, alkaloids, phenols, and essential oils) [8,9]. Bioactive compounds in herbaceous plants positively affect the functioning of the cattle digestive tract (modulation of rumen fermentation, regulation of digestive enzyme activity, improvement of nutrient digestibility) and health (strengthening of the immune system, antioxidant, and antiparasitic effects) [10,11].

In recent years, there has been a growing trend in the public sphere toward positive perception and greater consumer demand for animal products, including milk and meat, from animals reared in semi-intensive or organic farming systems [12]. This is due to increased consumer awareness linked to nutrigenomics and the positive impact of so-called functional foods on human health [13]. The observed trends are mainly related to the conviction of the higher nutritional value of such products and better welfare and environmental standards compared to raw materials and products obtained from animals reared in intensive production systems [14,15].

The study results confirm the correlation between nutrition and the type of fodder fed, and the quality of milk and meat, including protein, fat content, and fatty acid profile. Pasture feeding of dairy and beef cattle positively influences the content of essential fatty acids (EFAs) and conjugated linoleic acid (CLA) in animal products, which have beneficial effects on human health (stimulation of the immune system, anti-atherosclerotic and anti-cancer properties). In addition, pasture sward has higher levels of vitamin E and provitamin A (β-carotene) compared to conventional feeds, so during the summer feeding season on organic or pasture-fed farms, increased content of these vitamins in milk and meat is observed [14,16,17].

The quality of livestock products obtained from pasture-fed animals is correlated with the feeding of excellent pasture sward, and this, in turn, among other things, depends on grazing management. Over the past few decades, the way pastures are used has changed considerably. Currently, several grazing systems (continuous and rotational) are used in grazing management to achieve satisfactory production performance and excellent raw materials and animal products [18–20].

However, in addition to several advantages of pasture feeding, related to the ability of cattle to consume good quality roughage, the positive impact on animal welfare, and the quality of the products, unfortunately, there are also some disadvantages. Pasture feeding is undoubtedly more time-consuming and labor-intensive in some respects (including animal monitoring and grazing management) compared to keeping cattle in indoor or loose housing systems. Grazing livestock on the pasture also entails costs associated with purchasing and installing structural elements for the pasture fence and the designation of paddocks (Table 1). Conventional fencing has little flexibility, which increases the labor input involved in changing the area and location of the paddocks and translates into efficiency in utilizing the pasture—the exclusion of some sites due to periodic flooding [21,22]. In addition, physical barriers to grazing (electric fencing, metal mesh structures) can disrupt the natural landscape and the migration of some wildlife species, sometimes leading to permanent mutilation [23,24]. Moreover, virtual fencing might also be an opportunity for implementing grazing in formerly abandoned areas, protected habitats where physical fencing is prohibited [25], riparian areas [26], moorland [27], or sites prone to soil erosion [28].

2. General Concept of Virtual Fencing for Grazing Animals

Precision livestock farming is a concept in livestock farming using a variety of sensors and new technologies to improve the management capacity for big groups of animals [29]. One of those new technologies is the virtual fencing solution [30]. Improvements in grazing management should aim to optimize the soil-plant-animal relationship. To achieve this, a rotational grazing system that accurately allocates pasture is necessary. This will help to minimize wastage (over-allocation) or avoid negative impacts on pasture and cow performance (under-allocation) [31,32]. Virtual fencing has the potential to enhance the efficiency of grazing management. One major advantage is flexibility in managing stocking density. Virtual fencing technologies have expanded the possibilities for spatial and temporal control of animal grazing and nutrient transfer events [33,34]. It was first used to control the location of livestock in 1987 [35]. Virtual fencing is an enclosure, barrier, or boundary without a physical fence [27]. It allows real-time automation of grazing management, enabling the use of complex grazing systems to improve pasture and cattle management [36,37]. Virtual fencing is a part of digital technologies which may optimize animal productivity while minimizing environmental impacts [38,39]. Combining virtual fencing with decision support tools based on technologies for measuring environment variables, pasture availability, quality, and cattle performance provides the opportunity to create a step-change in the way cattle are managed [5,40].

The general idea behind the innovative grazing technology using virtual fencing based on an IoT system [41–43] is controlling animal behavior (stopping or changing the direction of movement) by employing stimuli (sound or very low electric current) generated by a collar-mounted device worn by the animals [34,44]. Virtual fencing works mainly by putting a collar on each animal which can administer auditory warnings (82 dB, 1 m) and low-energy electric pulses (0.2 J, 3 kV, 1.0 s). In addition, on-animal sensor devices are also being developed to assess behavioral variables such as time spent grazing or eating, ruminating, walking, lying, and drinking, and other cattle performance, health, and welfare-related parameters [45–47], including intake of pasture [48,49].

All virtual fencing technologies use more or less the same principle in which a collar with GPS is continuously tracking the position of the animal and checks this against the virtual borders set by the farmer and downloaded on the collar (Figure 1). If the animal approaches the virtual border, the collar will produce an audio signal whose intensity and tone scale increase when the animal comes closer to the border. If the animal does not respond to the audio signal, it will receive an electric pulse. The pulse has about 30 to 50 times less energy compared to a traditional electric fence, but still, it is enough for the animals to be considered unpleasant. The cycle of the audio signal followed by the electric shock is repeated one to two more times if the animal does not respond, the animal is indicated as 'escaped' (Figure 2), and the audio signals and electric pulses are switched off until the system is reset if the animal returns to the allowed zone. The farmer gets push messages when an animal receives an electric pulse or when it is 'escaped', and he can get live information on the position of each individual animal and the number of audio warnings. The collars have built-in solar panels to charge the batteries during the day.

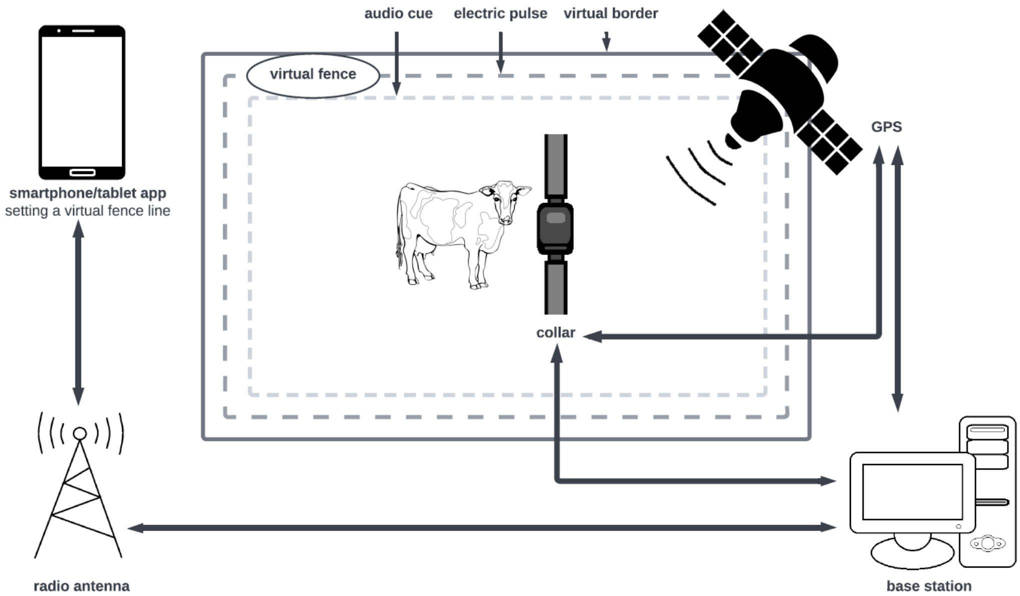

Figure 1. General concept of virtual fencing for grazing animals.

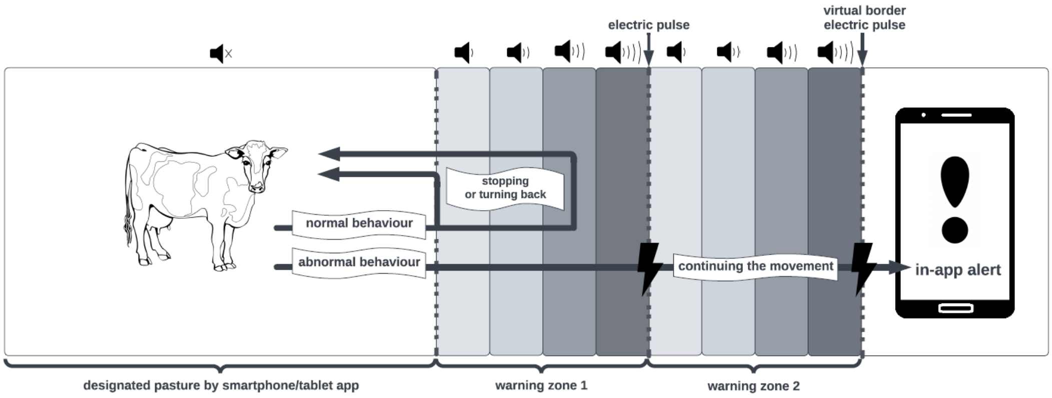

Figure 2. Possible response of grazing animals to virtual fencing.

The main advantages of grazing technology using virtual fencing include [24,50,51]:

- changing the area of virtual paddocks at any time of grazing,
- no negative impact on animal behavior (voluntary intake of pasture sward, ruminating, and resting),
- ensuring animal welfare (no stress affecting the quantity and quality of raw materials of animal origin),
- elimination of costs associated with the purchase and maintenance of structural elements of traditional fencing,
- time and labor cost reduction,
- online management of cattle herds in the pasture and the livestock building.

Table 1. Comparison of methods of pasture fencing and allocation of paddocks in terms of selected characteristics of animal pasture feeding.

Characteristic	Conventional Fencing [14,24]	Electric Fencing [52,53]	Virtual Fencing [51,54,55]
Safety	- safe for grazing livestock (occasionally getting stuck) - dangerous for wildlife	- safe for grazing livestock (occasional electric shocks) - safe for wildlife	- safe for grazing livestock; depends on the incentive generation system used (when animals cross the virtual fencing) - safe for wildlife
Animal grouping	- cumbersome; requires a lot of manual labor	- cumbersome; requires a lot of manual labor	- easy; remote via an app
Accessibility for staff	- difficult; requires climbing over the fence	- difficult; requires climbing over the fence	- very easy; no barriers to pass
Material costs	- high; construction and regular maintenance of the fence	- high; construction and regular maintenance of the fence; need to connect to DC power supply or electrizer	- high; depends on the type of virtual pasture fencing system (purchase of bands and software)
Labor costs	- high; animal handling and grazing monitoring	- high; animal handling and grazing monitoring	- small; remote animal control via an app
Flexibility in making changes to the fence	- very small; high labor input (dismantling and building a new fence)	- satisfactory; relatively small labor input to dismantle and set up a new fence	- high; fence location can be changed via an app at any time
Reliability	- high	- high	- satisfactory; depends on the device and app used
Public perception	- positive	- positive	- satisfactory; new technology requiring knowledge transfer to farmers, environmentalists, consumers

3. Innovative Systems of Virtual Fencing

Analysis of global patent databases revealed several solutions based on virtual pasture fencing technology using IoT (Table 2). The first ideas regarding using audible signals emitted by a collar-mounted device worn by an animal appeared around half a century ago but did not initially apply to livestock. The primary purpose of such systems was to control the behavior of companion animals (dogs and cats) with audible signals to discourage them from approaching or passing through the existing fence. Peck [56] turned the concept of virtual fencing into reality with his patent (December 1973, USA) describing a method and apparatus for controlling animals. Later in 1987, Peck's Invisible Fence manufactured the first virtual control devices for domestic livestock in the United States [35]. In this research, Peck's devices were used successfully to contain meat-type goats on leafy spurge (*Euphorbia esula* L.). Using modified and non-modified Invisible Fence equipment, Browning and Moreton [57] reported various levels of livestock control achieved in England among sheep, goats, cattle, and ponies between April 1990 and October 1992. However, cattle have been the animal of choice in all subsequent research applying various devices to establish proof of concept that virtual fencing is a viable method of animal control [58–66].

Currently, several solutions are available worldwide for dairy and beef cattle and small ruminants involving virtual pasture fencing [67]. All are based on avoidance learning using the cognitive activation theory of stress [68–70]. It turns out that animals learn to respond to a non-aversive sound stimulus to avoid an aversive electric pulse [52,71]. Successful learning occurs when the animal perceives the signals as predictable (acoustic signal warning always precedes the pulse) and controllable (the operational response to the acoustic signal prevents it from receiving the pulse). Thereby an acceptable welfare score is obtained. Campbell et al. [72] reported that the cattle learn after the initial learning period using an acoustic warning signal. It turned out that 50% of animals were learning to avoid the fence line based on the audio cue as a result of six interactions (on average) with the fence line. Animal behavior is predictable, and electrical stimulation can be avoided by responding to the acoustic signal [44,53]. However, cows have proved to have high diversity in their learning curve, with some animals displaying a consistent need for cues and stimuli even after a long period. Therefore, the negative sides of virtual fencing use include the potential risk of long-term animal exposure to an electric stimulus, which might have a negative effect on animal welfare [53,73], and public opinion [74,75]. Currently, the acceptance of virtual fencing technology by authorities and the public still needs to be proven and supported (boundaries for its correct use), and also the economic viability should be improved [20]. The total cost of technology limits the adoption of virtual fencing systems on commercial farms. According to the South Dakota Callemen's Association [76], traditional fencing currently costs around $9500 (7800 £) per mile when factoring in labor costs. GPS tower covers around 15,000 acres of land and costs around $10,000 (12,000 £). However, in the UK the cost of the system was estimated at 200,000 £ for 100 animals [27]. Moreover, another weakness is often the lack of the technological infrastructure in farms [77]. This includes network coverage and IT-related skills and understanding. Without this, farmers may find it difficult to trust hi-tech systems [78].

3.1. eShepherd

One of the virtual fencing technologies is eShepherd®, developed and commercialized by the Australian company Agersens (Melbourne, VIC, Australia) (acquired by the New Zealand company Gallagher). This system utilizes intellectual property that has been licensed and developed by the Commonwealth Scientific and Industrial Research Organization [44,50,79,80] and is commercialized for cattle. The cost of eShepherd technology is estimated as €60–90 for one collar and €5000 for infrastructure [81]. Virtual fencing uses the global positioning system (GPS) to assign location, movement, position, heading, and speed to cattle, and it communicates this information using neckband-mounted devices. Moreover, the GPS is used to specify the virtual fence boundary (separating inclusion vs. exclusion zones), which is transmitted to the unit using a radio frequency link. The cattle neckband consisted of a strap and hanging counterweight (total weight ~1.40 kg), and the unit (~725 g and 170 mm length × 120 mm width × 130 mm height) on the top of the animal neck and the solar-powered base station. The system controls animal behavior through a radio-controlled device. A transmitter on the neckband generates two types of stimuli—audio and electric [53,82]. An animal approaching the boundary of the virtual fence (determined by the mobile app) receives a signal to stop or change direction in the form of a sound of about 785 Hz. In addition, in the absence of the desired response to the auditory stimulus, an electric pulse with a relatively low voltage of 800 V is sent [24,54,83–85]. An audio cue followed by an electric pulse sequence was repeated if the animal continued through the fence line and into the exclusion zone. At this point, it should be added that in the case of conventional electric fences, the electric pulse voltage generated by the electrizer (so-called electric shepherd), among other things, is 2000 and 4000 V in summer and winter, respectively. When the animal reacts positively to the first signal (i.e., stops or turns back), the device does not generate another stimulus, i.e., an electric pulse.

The technology harnesses cattle's high potential for learning and remembering (known as an association—animals associate an audible stimulus and a potential electric pulse with the cessation of forward movement or a change in the direction of movement [86]. If an individual animal received a specified number of stimuli within a specific time frame, the device entered standby mode, and stimuli were not applied for a specified time frame (the specifics are commercially confidential, Agersens, VIC, Australia). The collar also included a grazing algorithm whereby if an animal gradually encroached on the exclusion zone by grazing (slow movement forward paired with stopping), an electric pulse followed after three consecutive audio cues. Campbell et al. [26] tested the effects of a virtual fence compared to an electric tape fence in containing eight groups of eight 12–14-month-old steers within a 6 ha area across eight separate paddocks for four weeks following one-week acclimation to the paddocks. The study indicates that virtual fencing technology effectively contains animals in a prescribed area across four weeks without substantial behavioral and welfare impacts on the cattle [87,88]. However, the eShepherd® virtual fencing system still requires investigation and adaptation into pastured-based dairy and beef cattle grazing herds. Prototypes of this system that are not yet commercially available have been used to control the location of small groups ($n \leq 20$) of grazing cattle [85], even when virtual fences were moved [89]. While early results are encouraging, several factors may diminish the effectiveness of the eShepherd® virtual fencing system in controlling the location of grazing cattle. They include greater stocking densities typical of pasture-based dairy systems (25–75 m^2/cow), which increase the probability of animals interacting with virtual fences, and greater motivation of lactating versus dry and beef cattle to feed [24], with hunger potentially undermining virtual fence efficiency [90]. It is necessary to quantify the effects of eShepherd® on the uniformity of pasture utilization (% of pasture consumed above a target residual of 1500 kg of DM/ha), as dry and beef cattle have been observed to avoid areas near virtual boundaries [54]. This research is of great importance, as pasture consumption plays a crucial role in determining profitability [33,91].

It is essential that new technologies in the animal sector at least maintain or improve animal welfare. To meet this standard, the design and implementation of new technologies must take into account and support the animal's learning abilities [53,92]. The majority of published virtual fencing trials have utilized the eShepherd® technology and have been conducted in Australia [26,89,90,93]. Those studies examined the suitability of virtual fencing and provided strong evidence that cattle are able to learn the system without negative impacts on animal behavior and welfare.

3.2. *Nofence*

In Europe, Brunberg et al. [94] conducted a study to determine the ability of ewes with lambs to learn a prototype virtual fencing technology produced by the Norwegian company Nofence (Nofence®, AS, Batnfjordsøra, Norway), which operates in a similar manner to eShepherd®. The differences are due to the design elements of the technology (solar panels for easy battery recharging, motion sensors, Bluetooth, and a GNSS receiver based on GPS and GLONASS and applications for diverse clients, and their PCs, smartphones, or tablets). The Nofence technology consists of a neck strap and collar with a battery with a total weight of ~1.45 kg positioned on the neck (153.5 mm length × 145.4 mm width × 54.2 mm height) [55,95,96]. The collar has an integrated GPS and sound and electric pulse generators which are connected to the neck chain using two electrodes. The estimated cost of one collar for virtual fencing in the Nofernce technology is €195 [81]. Nofence app can be used to establish virtual boundaries. When an animal approaches the virtual boundary, an audio warning with a rising pitch tone is emitted. If an animal approaches a virtual fence and does not respond to the audio warning (82 dB at 1 m), it will receive a short electric pulse (0.2 J at 3 kV duration = 1.0 s). If the animal responds appropriately by turning away from the virtual boundary, it will not receive any further stimuli (audio warnings or electric pulses). This system relies on the principles of associative learning and operant conditioning, which means that the animal should be able to control and predict it. The collar produces an electric pulse after all warning tones have been played. The warning tones increase in pitch and duration (from 5 to 20 s) depending on whether the animal keeps ignoring the warning or responds appropriately. The desired response depends on which collar mode is activated. In the teaching mode, the animal can stop the audio warning by simply turning its head. The collar-mounted accelerometer detects the movement and allows a prompt response to the animal's behavior in order to help it effectively learn the virtual fencing system. When the animal has correctly responded to 20 consecutive audio warnings without receiving an electric pulse, the collar will switch to operating mode. Following activation of the operating mode, the animal must move at least 2 m away from the virtual boundary towards the virtual pasture to stop the acoustic signal. In either mode, when the animal ignores the audio warning and continues walking towards the virtual boundary, it may receive up to three electric pulses if it does not respond appropriately to the warnings before each pulse. After that, the collar notifies the owner that "the animal has escaped" and continues to monitor its location. However, the animal will not receive any more audio warnings or electric pulses. When the animal that has crossed the virtual boundary returns to the virtual pasture, the collar will resume normal function without requiring any manual intervention [55,95–97]. Brunberg et al. [94] studied the use of Nofence on sheep, and the initial results indicated that this technology may not be suitable for small ruminants due to a high number of electric pulses, which could potentially compromise animal welfare. However, the first-generation collars used in the study had technical issues which resulted in the failure of the acoustic signaling before electric pulses were delivered. The Nofence virtual fencing technology is now commercially available for goats, cattle, and sheep in Norway and the UK, and further development is ongoing to improve the system. Still, work is underway to improve this system [97].

3.3. Vence

Vence® is another virtual fencing technology dedicated to cattle herd management, marketed by the US company Vence (Vence Corporation, San Francisco, CA, USA). This technology controls animal movement, designates virtual paddocks, and monitors cow welfare. The solution uses advanced GPS tracking to monitor the location of animals in the pasture using mobile devices with Android or iOS [98–100]. Moreover, Vence® is deployed in large-scale operations with over 500 animals and has been proven effective on small ranches of a few hundred hectares and large ones with hundreds of thousands of hectares. The virtual fencing is created by Herd Manager based on GPS coordinates. In this system, the end user communicates with a solar-powered base station through a cellular link using the Herd Manager software platform. The base station sends radio signals to the GPS collar worn by the animal, communicating user-defined coordinates of virtual boundaries and other information. The estimated cost of one collar for virtual fencing in the Vence technology is $35 [76]. The collar is powered by a lithium battery and tracks the animal's location at intervals specified by the user. It also has a speaker for auditory cues and two metal electrical contacts that are spaced 5 cm apart. The collar is equipped with a weight ballast that ensures that the electrical contacts only touch one side of the animal's neck. This means that when the animal receives an electric stimulus, it should turn away from the stimulus, changing its direction away from the virtual boundary. When an animal approaches a virtual boundary, it will first receive an auditory cue ("auditory zone"), and if it continues in the undesirable direction (entering the "electric stimulus zone"), it will receive a mild electric stimulus. The user can define the spatial locations of the auditory and electric stimulus zones. When an animal moves into the audio zone, it hears an electronic tone that lasts for 0.5 s, followed by a 1.5-s pause. This pattern is repeated until the animal leaves the auditory zone. When the animal enters the electric stimulus zone, it receives a 0.5-s shock (at a voltage of 800 V), followed by a 1-s sound stimulus and then a 3.5-s pause. If the animal remains in the electric stimulus zone, the pattern will repeat up to 20 times, after which the animal will not receive any auditory or electric stimuli for 3 min. If the animal stays in the electric stimulus zone for more than four cycles, the collar will be disabled, and all cues will stop unless it is remotely reactivated by the end user. The collar transmits animal location data to the base station, which then sends it to cloud-based storage within the Herd Manager platform. Boyd et al. [100] evaluated virtual fencing for excluding cattle from burned areas within small pastures in the sagebrush steppe of southeast Oregon. The study suggests that virtual fencing technology is largely effective, but it does not fully alter animal distribution for exclusion of cattle from burned areas. Moreover, compared to standard wire fencing, one might say that virtual fencing is largely but not entirely effective and fails on an individual animal basis. Boyd et al. [100] have proposed that there are many other potential applications of virtual fencing technology for precision rangeland management. For example, it could be used to create exclusion or inclusion zones for patch grazing systems or exclusion zones for avoiding certain areas during certain seasons, such as areas with poisonous plants. Virtual fencing could also be used to exclude animals from riparian areas in order to protect anadromous fish spawning habitat or riparian woody plants during the fall. However, further research is needed to more fully understand the potential utility of virtual fencing in rangeland cattle production systems, particularly at larger spatial scales and in more complex topographic environments.

3.4. Halter

New Zealand-based Halter has developed Halter® based on patented Cowgorithm®, which controls animal behavior based on audible, electric, and vibration signals and enables health monitoring based on body temperature measurements [65,101]. A neck-collar and combined head-halter (collar-halter) device was designed to carry the electronics, batteries (6 V, 4.2 Ah Panasonic lithium batteries), and stimuli-providing equipment, including audio, vibration, light, and electrical stimulation (of a linear range of 1–10 s duration and 600–4000 V). The neck collar was made from 100-mm-wide nylon webbing and contained compartments for the electronics box, GPS, radio antenna, and two batteries. The wiring for the radio and GPS antenna was routed through pockets in the collar to the top of the animal's neck to ensure optimal reception. The batteries and electronics were located at the bottom of the animal's neck. The weight of the batteries, which were on the heavier side of the electronics box, helped to balance the collar and prevent it from rotating around the animal's neck. External wires were connected from the electronics box to the head halter once the collar and head halter had been fitted to the animal. Bishop-Hurley et al. [65] investigated whether auditory and visual cues could be applied to control cattle behavior using virtual fencing technology. The treatments involved a combination of cues (audio, tactile, and visual stimuli) and consequences (electrical stimulation). The treatments included: electrical stimulation alone, audio and electrical stimulation, vibration and electrical stimulation, light and electrical stimulation, and live electric fence (6 kV) and electrical stimulation. The cues were delivered for 3 s, followed immediately by a 1-s electrical stimulation (consequence) at a voltage of 1 kV. The experiment results demonstrated that virtual fencing has the potential to control cattle in extensive grazing systems. However, larger numbers of cattle need to be tested to derive a better understanding of the behavioral variance. Further controlled experimental work is also necessary to quantify the interaction between cues, consequences, and cattle learning.

Table 2. Technical comparison of virtual fencing technologies used worldwide in ruminant feeding pastures.

Characteristic	eShepherd® [84]	Nofence© [95]	Vence® [98]	Halter® [101]
Audio signal	- frequency 785 Hz	- sound intensity 82 dB	- present - no available technical data	- present - no available technical data
Electric pulse	- present - voltage 800 V - lasts less than 1 s	- present - voltage 3000 V - lasts 1 s	- present - voltage 800 V	- present - voltage 600–4000 V - device generates vibrations - lasts from 1 to 10 s
Satellite navigation system	- GPS	- GPS and GLONASS	- GPS	- GPS
Battery	- solar panel charging	- solar panel charging	- solar panel and lithium battery charging	- lithium battery charging
Mounting	- neckband	- neckband	- neckband	- neckband
Device weight	- approx. 1.4 kg	- approx. 1.5 kg	- no available technical data	- no available technical data
Cost of 1 collar	- €60–90	- €195	- €33	- no data

4. Development of Virtual Fencing Technology

Further research and development work is underway to improve virtual pasture fencing technology by expanding the ability to monitor daily activity and animal health to reduce the costs of manufacturing and using complete systems. In addition, it is worth noting that the systems described earlier are in the early stages of research and development without any support facilities. Taking into account the above limitations, which prevent the application of this type of technology on farms in our country, the Department of Grassland and Natural Landscape Sciences of the Poznan University of Life Sciences launched a project entitled "Sourcing top-quality culinary beef based on pasture feeding of cattle controlled by IoT system" (acronym: ProEcoFarm) co-financed under the 2014–2020 Rural Development Program. The project's main objective is to produce top-quality culinary beef based on a model of farming suckler cows in a pasture-based feeding system on extensive grasslands located in high nature value areas using an Internet of Things (IoT) system. The issue addressed by the project is particularly important from the point of view of cattle grazing in high nature value areas, where it is often impossible to build conventional fences and constantly monitor the daily activity of animals. Furthermore, remote control of the cattle herd using collar-mounted devices will also make it possible to exclude areas with protected plant or animal species from grazing without building physical barriers. The benefits of directing grazing animals to appropriate landscape niches are also highlighted by Stevens et al. [34] and Greenwood [5]. The R&D efforts aim to develop a much cheaper but equally innovative system for determining virtual fencing and grazing paddocks for suckler cows of various beef breeds and calves. It is worth noting that an essential part of the technological innovation is determining grazing areas according to the cattle's feeding group classification. In addition, the developed technology will allow changes to the grazing area of individual animals at any time using a mobile app facilitating herd management and improving the efficiency of grazing sward use.

5. Conclusions

Precision livestock farming is increasingly being used in pasture feeding systems. Especially the evolving virtual fencing designed for grazing dairy and beef cattle opens up new opportunities for using available pasture land. Virtual fencing has the potential to reduce the amount of labor required for fencing, increase the flexibility of fencing to adapt to changing pasture conditions, improve precision and efficiency, and provide more options for grazing management. However, this innovative technology should be further developed, and improvements should include decreasing the total costs of the system and increasing its application to other technological groups of ruminants, e.g., suckler cows with calves, increasing the efficiency of the system operation in large areas and a larger number of animals. Currently, research is being carried out on the response of various cattle breeds to the use of virtual fencing technology, as well as studies on the effectiveness of grazing management using virtual fencing in high nature value areas. Recent advancements in electronic communication and device design have the potential to significantly improve the effectiveness of virtual fencing technology while lowering costs. However, further evaluation is needed to determine their usefulness in precision agriculture systems.

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