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CHALLENGES AND OPPORTUNITIES FOR PRECISION LIVESTOCK FARMING APPLICATIONS IN THE RABBIT PRODUCTION SECTOR

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Abstract: Precision livestock farming (PLF) is an established field in many livestock sectors. However, when it comes to rabbit production, it is still emerging. Nevertheless, we believe that the rapid advancements in sensor technologies, data analytics and automation we are witnessing can bring significant and transformative opportunities to the rabbit farming industry. Within this context, this paper explores the potential use of PLF for the rabbit sector. We start by briefly reviewing the current state of the art of PLF applications in other livestock sectors, such as dairy and pig farming, focusing on remote sensing solutions. Then we outline how different technologies can potentially be adapted for rabbit production. Recent rabbit research studies that implement PLF-like technology are then reviewed. We finalise by discussing the challenges of implementing PLF in rabbit farming, including the need for tailored solutions that consider rabbits' specific behavioural and physiological characteristics. When considering the future impact of PLF, early disease detection probably offers the highest potential for rabbit production. Being able to automatically detect early signs of digestive disorders around weaning, particularly in large group-housed growing rabbits where disease spread is a concern, would represent a significant step forward. Additionally, PLF tools can enhance rabbit breeding and genetic programmes by providing detailed and accurate individual phenotypic data. Data can be then used to better define animal management practices that promote positive experiences and affective states, reducing negative social interactions. Besides, precision feeding models could contribute to enhancing feed efficiency for both growing and reproductive rabbits, reducing the negative environmental impact of feeding. To this end, camera monitoring, sound analysis, electronic feeders, accelerometers and other biometric and physiological monitoring technologies can be utilised. The integration of PLF technologies promises to support farmers in meeting the increasingly stringent welfare regulations across the European Union, ultimately enhancing the sustainability and profitability of rabbit production systems. Further research is needed to address the challenges that remain in developing and validating reliable algorithms so that sensors can be used more effectively in diverse rabbit farm conditions.

Key Words: rabbit farming, precision livestock farming, remote sensing, animal monitoring.

PLF FOR RABBIT PRODUCTION – AN EMERGING FIELD

Precision Livestock Farming represents a modern information-driven approach towards farm animal production. While technology is an important part of PLF, technology should never be the core focus, which should instead be the value that PLF creates for the farmer and animal. While research in the field of PLF has been developing for over 30 yr now, with many scientific publications in traditional animal production areas, there is still much work needed to confidently take this technology towards producers in many cases. In the smaller production sectors, such as rabbit

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production, PLF has barely made an impact to date. Nevertheless, with the rapid advancements we see in sensor technologies, data analytics and automation along with the experience from the other production sectors, PLF in the rabbit production world has the potential for much faster development. This review seeks to give an overview of PLF and to speculate on the potential for PLF technology in the rabbit sector.

PLF centres around the collection and exploitation of data to support animal husbandry practices. In all animal production sectors, data is becoming more effectively used in the daily management of animals. Record keeping of daily farming activities has long been used by farmers to keep account of how the farming system is running. With the transition from paper to the digital era, farmers now see more opportunities to combine and integrate data all over the farm. With many implementable affordable software solutions being available, the decision-making of many farmers can be significantly improved. However, these tools have a key limitation. Despite being digital, they often rely on manual inputs from the farmer (or farm workers) to keep account of what is happening. Problems such as forgetting to input data and mis-inputs regularly occur, as farmers are, after all, human like us all. Furthermore, when the farmer is not around no data is being collected. The eyes, ears, and perhaps nose of the farmer are currently not represented at the times that they are not there. This is where more advanced PLF tools, which exploit sensor technologies, can make a significant impact.

Until now, PLF research and development has focused on well-established, traditional farming sectors. Rabbit farming presents unique and interesting challenges that make it an ideal candidate for a new wave of PLF developments. For example, when presented with housing-related stressors, the health and welfare of the rabbits can become quickly compromised (Trocino and Xiccato, 2006). Stress responses can be difficult to detect by workers through direct observations (Verga *et al.*, 2007). Given the scale of modern rabbit farms, a more advanced technological approach to monitoring and managing rabbit health and welfare is therefore becoming interesting. Integrated environmental control and automated health and welfare monitoring are just a small list of things that have the potential to address key challenges facing the sector. Furthermore, the integration of actuators that can tailor nutrient delivery towards the specific needs of each rabbit can reduce the environmental impact of feeding while enhancing gut health. Developing PLF technology in the short term can facilitate pathways towards reducing the negative impacts of the production system. It will not only assist farmers in meeting increasingly stringent welfare regulations across the European Union (EU), but also the general sustainability and profitability of their operations.

In this paper, we review the technology needs of the rabbit production sector. Focusing on remote sensing solutions, we follow this with an overview of the specific PLF breakthroughs in dairy and pig production sectors. We then explore the recent uptake of PLF technology in rabbit research and hypothesise future applications of this technology.

PRODUCTION CHALLENGES FACING THE RABBIT SECTOR FOCUSING ON HEALTH, WELFARE AND PRODUCTIVITY

The rabbit sector in Europe is rapidly changing. These changes have greatly shaped the producing segment, impacting on its sectoral structure. As in many other livestock sectors, but in this case, with a slight time delay, the rabbit farming sector has been undergoing a strong professionalisation and renovation process in the last decade (Figure 1). This has resulted in a concentration of farms, particularly those large in size, and the disappearance of smaller, less competitive ones. This situation, however, also presents a perfect opportunity for implementing transformative innovations and improvements in the rabbit farming system.

According to the European Commission (2017), new rabbit farms generally have over 1000 does (in some cases over 5000 does), whereas farms housing around 500-600 does were the most common type in the leading producing countries in Europe (Spain, France and Italy) in the previous decade. Large-sized rabbit farms require managing and supervising an increasing number of animals, with a limited workforce, seeking greater efficiency in resource utilisation and profitability, as well as improved technical knowledge. Managing a large number of rabbits might be complicated and requires close monitoring. Rabbits can exhibit a range of behavioural, physiological and emotional responses in a relatively short period. This is because they are animals that are constantly vigilant, fast-moving, and mentally occupied with the potential threat of predators (Monclús and Rödel, 2008).

Figure 1: Conventional housing system for rabbit does with automatic feed distribution systems, wired cages above manure pits, featuring mechanical ventilation (left) and natural ventilation (right). Source: Joan Rosell, personal archive (2008–2018).

Nevertheless, this scaling up of the sector contrasts with the declining global production metrics, slaughter rates, meat production and census numbers, as well as exports in the EU rabbit sector. Rabbit meat consumption levels are continuously decreasing. This might be linked to changing consumer trends, a loss of traditional habit of eating rabbit meat in young people, the increased perception of rabbits as pets, and consumer price competition at the retail level compared to other meats (European Commission, 2017). However, the rabbit farming system has proven to be resilient. Globally, rabbit systems are diverse and rather atomised, with small-scale farms coexisting with the above-mentioned conventional large-scale operations. For small-scale production, different systems are available worldwide, such as open naturally-ventilated sheds in countries with a warm, tropical climate like Brazil (Machado and Simões, 2024). Other niche small-scale examples are based on organic, pastured rabbit systems (Gidenne *et al.*, 2024) or agroforestry models (Savietto *et al.*, 2023), as in France (Figure 2). In the EU, 34% of rabbit meat consumption comes from small-scale backyard farms (European Commission, 2017) – a non-negligible share. In a sector as complex and diverse as rabbit farming, the application of knowledge, technological innovation and the implementation of digital tools can help improve farm technical management and animal care. This can contribute to both intensive and extensive production models, covering the entire range of intermediate production scenarios in rabbit farming worldwide.

Similarly to all livestock sectors, rabbit producers must also comply with strict regulations and consumer demands: i.e. the reduction in the use of veterinary antimicrobial substances, the fulfilment of environmental regulations on emission reduction and improvements in animal welfare. Enhancing on-farm rabbit welfare is particularly challenging, especially given the current transition towards cage-free housing systems as foreseen by the European Citizens' Initiative 'End the Cage Age' (European Commission, 2021). Although alternatives to cage housing exist for other animal species (i.e. floor systems, multi-tier aviaries and free-range for laying hens, and free-farrowing, multi-suckling and fully outdoor systems for sows), there are no well-defined housing alternatives for rabbits, particularly for rabbit does. In 2020, the EFSA AHAW Panel (2020) identified several health and welfare concerns across different rabbit housing systems used in Europe. According to this report (based on a 2-step expert knowledge elicitation process) the welfare of rabbits was likely to be lower in conventional cages compared to enriched cages, elevated pens and organic or outdoor systems. Thus, the sector is strongly in need of creative solutions and advanced multidisciplinary tools that can help farmers comply with evolving regulations and assist them in the cage-free transition.

Figure 2: Grazing rabbit system with fixed padock ((c) INRAE, T. Gidenne). Source: Gidenne *et al*. (2024).

Despite these regulatory advances, practically all rabbits in the EU are housed in cages (112 million) (CIWF, 2020). In this context, key behaviour-related welfare issues that need attention in rabbit farming systems include restriction of movement, resting problems, inability to express maternal, positive social and gnawing behaviour, and the occurrence of abnormal behaviour and fear (EFSA AHAW Panel, 2020). With high levels of animal confinement, rabbits cannot express their natural behaviour freely, which could lead to abnormal behaviours and stereotyped conducts. Furthermore, confined individual housing does not allow social contact and other intrinsically motivated behaviours that could contribute to their positive welfare.

However, shifting towards non-cage systems that allow animals more freedom of movement and stimulate positive behavioural expressions involves trade-offs. Consequently, there are still numerous factors that can be impacted (positively or negatively) by the transition to cage-free systems in rabbit production. These factors include not only increased investment in housing and production costs, but also require a complete evaluation of rabbit's behavioural needs under this new environment. Furthermore, cage-free systems place specific demands on the management which requires well-trained technical staff to successfully manage the farm and the animals in non-caged large flocks or small groups of animals.

Additionally, rabbit systems with greater freedom of movement exhibit lower feed efficiency, which may impair animal productivity (Machado *et al.*, 2019; Matics *et al.*, 2019), compared with systems where the physical activity of the animals is lower. Additionally, group housing complicates precision nutrition and providing individual tailored feeding for rabbit does, which may affect their performance, welfare, health and lifespan (Martínez-Paredes *et al.*, 2022). Using the population-feeding approach, individual variations according to physiological state, body condition, genetics or animal health may be overlooked (Pomar and Remus, 2019). In fact, rabbits are the only zootechnical species where generally, all reproductive animals (lactating and non-lactating) use a common feed, lacking *ad hoc* nutrition according to the female's physiological status. Some exceptions in certain farms include a specific rearing diet for first-lactation does or a pre-weaning diet. Moreover, although group rearing is certainly the best choice to satisfy rabbit social behaviour in growing animals; in breeding does, continuous group housing can lead to aggressive interactions, injuries, stress and sometimes death (Trocino and Xiccato, 2006). This occurs when competing for resources and to establish a social hierarchy. Pérez-Fuentes *et al.* (2020) and Szendrő and Dalle Zotte (2011) reported aggressive interactions leading to increased mortality rates, in both does and their kits, when rabbit does were permanently housed in groups. In part-time systems, the most convenient group size and timing for grouping are still under debate.

As regards health aspects, cage-free systems can be linked to a greater health risk and transmission of diseases which can negatively impact animal welfare and farm productivity. In growing rabbits, the risk of intestinal health disorders (e.g. epizootic rabbit enteropathy, ERE) is multiplied when the number of animals housed together is increased (Birolo *et al.*, 2019). Digestive disorders during the growing phase remain one of the main causes of mortality in rabbit farms (Licois *et al.*, 2005). This digestive pathology frequently starts affecting rabbits from 3 to 7 wk of age. The ERE can lead to morbidities of 90% and mortalities of 80% (Bäuerl *et al.*, 2014). The first clinical signs of illness include reduced activity and feed consumption due to a slowdown in the intestinal transit rate and abdominal pain. These early signs of ERE, however, are difficult to detect individually in group housing, and flocks are frequently diagnosed and treated only when final-stage diarrhoea becomes evident. Controlling these digestive disorders remains a challenge, often necessitating feed restriction and antibiotic treatment. This could increase the need to use antibiotics in a context demanding a reduction of their use. Finally, the type of housing can also affect air quality, impairing the respiratory health of both animals and workers. Although concentrations of suspended inhalable and respirable dust, bioaerosols (Adell *et al.*, 2012) and gases (Calvet *et al.*, 2011) are low in rabbit farms compared to those of other animals, their production, aerosolization or both, is strongly related to increased animal activity, access to litter or bedded floors (Cambra-López *et al.*, 2010).

In commercial farms, despite the modernisation of rabbit rearing practices, housing conditions and other improved farm and animal management practices, mortality rates remain high and disease outbreaks affecting numerical productivity persist (Huneau-Salaün *et al.*, 2015). Although disease resistance, longevity and resilience have been included in some breeding programmes, particularly in breeding does (García *et al.*, 2021), there are still important health issues causing animal pain, discomfort, mortality and increased production costs to control the disease (EFSA AHAW Panel, 2020).

Some examples of health issues and disease-causing serious consequences for the health and welfare of rabbits are described herein. Besides disorders of the digestive system in growing rabbits, in rabbit does, the main causes of death or illness are related to respiratory conditions (mainly pneumonia), followed by digestive problems (such as enteritis-diarrhoea and mucoid enteropathy) (Rosell and de la Fuente, 2009; Rosell and de la Fuente, 2016). Pasteurellosis is highly prevalent. Consequently, health monitoring for signs of rhinosinusitis —such as sneezing, since rabbits do not cough, nasal secretion or difficulty in breathing— is an important task to diagnose clinical rhinitis (Rosell *et al.*, 2023). Early diagnosis can avoid its progression, which can lead to severe pneumonia and death. Other key health-related welfare issues that need attention in rabbit farming systems include pododermatitis and other, skin problems, mastitis, reproductive and neonatal disorders, cold stress, and most notably heat stress —as rabbits are fur animals (EFSA AHAW Panel, 2020). All these problems can greatly impact the animal's reproductive life cycle, which is on average around 6 kindlings per doe (Rosell and de la Fuente, 2009).

Table 1: Compilation of PLF applications in rabbit farming. Adapted from Cambra-López *et al.* (2024).

Monitored trait	Sensor used	Reference
Counting rabbit populations	Thermal camera, camera traps	Psiroukis *et al.* (2021), Latham *et al.* (2012)
Body weight, body surface and length	Camera	Giersberg *et al.* (2015); Negretti *et al.* (2007)
Body temperature	Thermal camera and implantable temperature loggers	Agea *et al.* (2021); Chen *et al.* (2023); Jaén-Téllez *et al.* (2021)
Feed intake	Camera and RFID[1] systems	Duan *et al.*, (2022); Piles *et al.* (2024); Sánchez *et al.* (2024)
Physical activity and specific behaviours	Accelerometers and camera	Adedeji *et al.* (2023); Ipek *et al.* (2023); Sánchez *et al.* (2022); Studd *et al.* (2019)

[1]Radio frequency identification.

WHAT HAS BEEN DONE IN PLF IN OTHER SECTORS TO SUPPORT ANIMAL HEALTH, WELFARE AND PRODUCTIVITY

PLF leverages advanced Information and Communication Technology (ICT) systems to achieve real-time monitoring and control applications. As already mentioned above, these systems can support farmers by automating the monitoring and assessment of animal health and welfare, and in the efficient management of large herds of animals. In the following paragraphs, we consider the main developments in sensing in PLF, mainly in dairy and pig farming, drawing out their key benefits and limitations. We focus on remote sensing, as this has proven to be an interesting tool for large-scale animal monitoring.

Camera-based monitoring

Camera technology has significant flexibility for PLF applications. For example, in dairy cow applications, cameras have been used to measure body conditions score (e.g. Liu *et al.* 2020) and cow behaviour concerning cow health and welfare (Chen *et al.*, 2021). The swine production field has seen regular improvements in computer vision-based weight monitoring since the original application by Schofield *et al.* (1999). However, in the current research environment, there is an intense focus on using computer vision to track animal movements in their pen environment, intending to detect abnormal behaviours and welfare challenges (Parmiggiani *et al.*, 2023). Recent studies have been able to develop technology to track these behaviours at an individual level, which can have a significant advantage for the animal breeding sector. While such work is progressing, it is largely challenged by the difficult conditions experienced in livestock buildings (Liu *et al.*, 2023). Currently, limited tracking of animals can be achievable once certain operating conditions for camera deployment are followed (e.g. overhead view, limited blockages and distortion). This technology will lead to rapid improvement in long-term health and welfare monitoring on the farm. Therefore, camera-based technologies are showing significant potential as a PLF tool and can find interesting applications in the rabbit production sector.

Sound monitoring

Sound analysis is increasingly being explored, particularly for animal health and welfare applications. The non-invasive nature of sound monitoring, combined with its ability to listen around corners during the day and night, makes it an interesting tool. While various applications of sound analysis exist, in pig farming sound analysis has been able to monitor respiratory health by using coughing sounds as a primary indicator (Exadaktylos *et al.*, 2008). Additionally, pig vocalisations, including screams, grunts and coughs, have also been correlated with stress and environmental comfort, providing insights into the pigs' physical and emotional states and ultimately their welfare (Briefer *et al.*, 2022; Nan *et al.*, 2022).

However, sound analysis in typical PLF applications faces important challenges, primarily when it comes to accurately interpreting sounds in noisy farm-building environments. Background noise coming from machinery and overlapping vocalisation from other animals can interfere with the clarity of sound recordings and sometimes makes it difficult to extract meaningful data (Carpentier *et al.*, 2019; Nan *et al.*, 2022). Nevertheless, the potential of sound analysis to enhance animal health monitoring and welfare assessment in commercial farming is improving greatly, with commercial solutions already available. As technology evolves, it is likely to become an even greater part of animal production, with potential transferrable learnings towards the domain of rabbit production.

WHAT ARE THE OPPORTUNITIES FOR PLF DEVELOPMENT IN RABBIT PRODUCTION

Sensing technology can offer enormous potential to help address current challenges facing rabbit farming that can contribute to maintaining animal productivity, farm profitability and sustainability. The potential is immense, and technology could serve as an aid in various fields within rabbit production. However, very few technologies are being developed and/or validated for this species. Table 1 summarises the state of the art of some PLF applications in rabbit science.

In general, although scientific advances in research are sometimes sufficient, implementation is still limited across most species and is particularly pronounced in the rabbit sector. Implementation requires combining scientific advances with practical technological innovation and transfer. To this end, collaboration amongst research, the rabbit sector and industry is fundamental. In the following paragraphs, we delve deeper into the technology applications that have been considered so far in rabbit science.

Monitoring the presence of rabbits

Monitoring rabbit populations is one important application of sensing technology for ecological purposes. Psiroukis *et al.* (2021) used Unmanned Aerial Vehicles (UAVs) equipped with thermal cameras to monitor and count free-range rabbit populations on the Greek island of Lemnos. This research demonstrated how effective UAV-based thermal imaging accurately estimate rabbit populations, particularly over varied terrains and during nocturnal hours. The study also highlighted the advantages of non-invasive technology to provide reliable data for wildlife management. Complementing this, Latham *et al.* (2012) studied the use of camera traps for monitoring wild rabbit populations in Otago, New Zealand. They showed that these traps are also effective for assessing the success of pest control operations. These technologies can certainly be used to improve decision-making in both agricultural and conservation contexts, although their transferability to commercial rabbit farming is limited.

Physical activity in natural conditions

Recent research currently shows how monitoring techniques can provide insights into rabbit behaviour, which is important given that this could be used as part of welfare assessment in intensive production systems. Adedeji *et al.* (2023) developed a deep learning-based approach to classify rabbit behaviours. They utilised state-of-the-art computer vision models to classify various rabbit behaviours, such as digging, eating and social interactions, with an accuracy of up to 86%. While this work indicates how computer vision could provide information on rabbit behaviour, the use of public datasets that did not represent rabbit farming conditions restricts agricultural use. Another study on the free-range behaviour of snowshoe hares (Studd *et al.*, 2019) employed a combination of accelerator and acoustic analysis to classify behaviour in free-ranging conditions. The study demonstrated how wearable sensors could effectively monitor these activities in their natural environment, and specifically showed that snowshoe hares decreased their activity in response to moonlight conditions. In summary, these studies bring into perspective that behavioural monitoring could be used to assist in understanding behavioural dynamics in free-range situations. These studies have particularly demonstrated the feasibility and effectiveness of remote monitoring (camera and microphone) technologies in capturing and analysing lagomorph behaviours. This is interesting, given the opportunities and developments that image and sound technologies have seen in other farming sectors.

Feeding and social behaviour in farming conditions

In intensive rabbit farming situations, the conditions are far different to those experienced in the natural environment. Ipek *et al.* (2023) studied rabbits in a realistic farm housing environment using computer vision. They considered agonistic interactions among group-housed rabbits, which is a key challenge the animals face when forming a social hierarchy in group housing scenarios. In their analysis, they were able to identify and quantify aggressive behaviours indicative of stress and poor welfare conditions. Another study carried out by Piles *et al.* (2024) specifically focused on capturing novel phenotypes of feeding and social behaviour that linked with rabbit growth and feed efficiency. Their findings suggest that feeding behaviour and social interactions are connected with growth patterns and optimise feed use. They demonstrate how monitoring of certain production and behavioural traits can enhance both efficiency and welfare in rabbit production systems.

With respect to understanding and managing feed efficiency, Sánchez *et al.* (2024) introduced the eFeederRab, an electronic feeder designed to measure feed intake in group-housed rabbits. This technology allowed precise monitoring of individual feed consumption and could be used to develop more sustainable nutrition strategies for rabbit production. The ability to monitor and adjust feed intake on an individual basis has long been a big ambition of

Figure 3: An electronic feeder prototype specifically designed for growing rabbits developed in IRTA's nucleus farm at Caldes de Montbui, Spain (left: Sánchez *et al.*, 2024) and another prototype developed for breeding rabbit does at the experimental farm in Universitat Politècnica de Valencia, Spain (right: Cambra-López *et al.*, 2023).

PLF and is at the core of enabling more sustainable and cost-effective farming practices throughout all sectors. Some examples of automatic electronic feeders used for monitoring feeding behavior for research purposes are illustrated in Figure 3.

Another interesting investigation was carried out by Duan *et al.* (2022), who quantified an estimate Remaining Feed Weight (RFW), which is the amount of feed left in rabbit feeders, intending to monitor the health of rabbits. The model combined a deep learning approach (Mask RCNN) for feed segmentation with technical improvements to image processing (more precise boundary detection) as well as weight estimation. The system achieved high accuracy, with a correlation coefficient of 0.97 and a mean absolute error (MAE) of 10.51 g. In practical farm applications, the study found that higher RFW, indicating reduced feed intake, was strongly correlated with increased rabbit mortality, thus potentially serving as an indicator of rabbit health.

Taken together these studies highlight potential PLF approaches towards integrated health and production monitoring of rabbits on farms.

Monitoring physiological responses of rabbits with sensors

Recent studies on body temperature measurements in rabbits show the strengths of both infrared thermography (IRT) and telemetry sensor systems. Agea *et al.* (2021) and Jaén-Téllez *et al.* (2021) both evaluated the use of IRT as a non-invasive tool for assessing stress-related temperature changes in rabbits. Agea *et al.* (2021) used IRT to identify rabbits with lower stress responses. Interestingly, their study found that rabbits with lower variability in litter size exhibited smaller increases in body temperature following a stressful event. Jaén-Téllez *et al.* (2021) also utilised IRT to monitor rabbit stress, but instead looked at the impacts of handling and environmental stress production. They showed that, while stress led to increased feed intake and growth rates, the rabbits presented less efficient feed conversion as a result. This indicates the importance of stress on productivity, as well as the capability of IRT to capture this information.

Complementing these findings, Chen *et al.* (2023) developed a telemetry sensor system for continuous, real-time monitoring of body temperature (subcutaneously implanted) in rabbits, to provide a detailed and long-term perspective on rabbit health. The authors showed the telemetry system to be reliable and effective in monitoring temperature deviations beyond expected values. This system can be particularly useful in detecting health issues early, without the need for frequent handling, which can be a source of stress in and of itself. While practical challenges remain, such as how to ensure an appropriate distance between the animal and the antenna, the authors were able to demonstrate that the customised telemetry sensor system could offer useful insights.

Taken together, technologies that monitor the physiological responses of rabbits can give farmers new ways to monitor rabbit welfare accurately. Telematic approaches can also potentially facilitate longer-term monitoring and have potential applications in rabbit farming.

Monitoring the dimensions of rabbits and space utilisation

As already highlighted in previous sections, camera technology has a significant potential to enhance the understanding of animal productivity, with a key example being automated weight analysis. In rabbit production studies by Negretti *et al.* (2007) and Giersberg *et al.* (2015), computer vision methods and planimetric measurement methods were used to accurately assess physical traits and space requirements of rabbits in commercial farming systems. Negretti *et al.* (2007) showed that morphological traits and body weights could be accurately measured using image analysis, which is more reliable compared to manual measurements. They also defined a new parameter called "body side surface (BSS)" to estimate live and carcass weights, showing high correlation coefficients (R^2=0.87) with live weight. This technology can foster more efficient and accurate breeding management practices by reducing the need for manual measurements.

Another interesting study was done by Giersberg *et al.* (2015), who looked at the space occupied by rabbits in different body positions, using the "KobaPlan" method as a basis for designing housing systems that meet welfare standards. They used a camera setup to collect images of rabbits in a controlled environment and then analysed these to determine the floor space occupied by rabbits in different postures (sitting and recumbent positions). They found that the floor space covered by rabbits increased linearly with body weight and that recumbent rabbits occupied significantly more space than sitting ones.

Taken together, these studies illustrate how camera-based technologies can provide tools for different design and monitoring applications, and thereby offer a comprehensive approach to improving both the welfare and productivity of rabbits. Leveraging these technologies can help rabbit farming achieve higher welfare in breeding and management than currently possible.

CONCLUSIONS AND OPPORTUNITIES FOR PLF DEVELOPMENT IN RABBIT PRODUCTION

The type and volume of information that we can handle through PLF technologies is expanding rapidly (i.e. individual identification of animals, their position, behaviour, live weight, body condition, body temperature, respiration rate, feed consumption, feed conversion and even emotions, with some attempts being made to measure pain and frustration). Data can be obtained using different sensing technologies, as described in the previous sections of this review. Therefore, outside of research, this information can help professionals in the rabbit sector, especially in key fields such as veterinary medicine, breeding, genetics and nutrition.

Regarding veterinary medicine, animal monitoring technology can help identify weak and unhealthy animals in real time, and on a 24/7 basis. In fact, one of the main opportunities offered by PLF in rabbit production is early disease detection. Early detection of signs of disease can help caretakers to take quick actions to reduce the impact of disease on the health of the animals. This application can be highly relevant in rabbit does (e.g. for example, to get an early warning of respiratory problems), but more notably in growing rabbits. Generally, all animals, including rabbits, when ill, reduce their daily feed and water intake and also change their activity patterns. Therefore, measuring feeding behaviour and water consumption, as well as the individual activity levels of growing young rabbits, could be used to develop an early warning system for potentially sick animals. This could potentially be done using electronic feeders/drinkers with radio frequency identification (RFID) systems, developing *ad hoc* vision-based monitoring models, tracking rabbit activity using accelerometers, and measuring other biometric and physiological variables (e.g. heart rate). This application could have enormous potential around weaning, when the likelihood of digestive disorders is the highest. Early disease detection enables targeted veterinary treatments for rabbits showing initial signs of illness, improving treatment effectiveness and supporting the rational, minimised use of antibiotics. This application is especially relevant for group-housed animals, where the risk of disease spread is sometimes higher than in other situations.

In terms of breeding and genetics, digital phenotyping allows for the continuous collection of hundreds of traits from many animals simultaneously, which can be recorded non-invasively and individually, even under field conditions. Individual phenotypic data can be used in rabbit breeding programmes, for instance, to enhance the adaptation of females to permanent and/or part-time group housing. Precision livestock farming tools could help evaluate management and breeding practices that promote positive experiences (e.g. grooming in rabbit females or play and exploratory behaviour in growing rabbits) and minimise negative ones (e.g. fear, boredom, pain and frustration). This could be done by measuring objectively specific rabbit behaviours, physiological responses and body or facial expressions. Cameras, accelerometers and sound analysis could potentially serve for this aim once the algorithms to do so are developed. These algorithms need to be calibrated to automatedly detect movement patterns and the frequency and type of social interactions to verify that animals exhibit desirable natural behaviours and to identify problems such as aggression. They must also be validated to ensure transferability across different farms and building types.

In the area of nutrition, the use of electronic feeders in rabbits would allow for continuous and automatic tracking of individual consumption (type and amount of feed), as well as the study of feeding behaviour (frequency, duration and feeding rate). This could furthermore enhance feed efficiency and allow for the adjustment to individual nutritional needs (both for growing and reproductive animals), towards the practical implementation of a tailored feeding system in rabbits. This application could be highly beneficial in group housing for does, as the formation of stable groups involves animals of different types (mothers and kits) and physiological states (lactating and non-lactating).

Finally, the potential of PLF tools to control indoor environmental conditions in rabbit farms (temperature, relative humidity and air quality, among others) should also be acknowledged as a valuable opportunity. This can be achieved through better integration between the ventilation and manure management systems. Such an approach could ensure optimal environmental comfort for the animals and, therefore, reduce the stress associated with unfavourable environmental conditions. Improved environmental control can lead to better productivity and health outcomes, benefiting both the animals and the farm's efficiency.

Although not exhaustive, these examples also highlight specific challenges where further research is undoubtedly needed in rabbit science. Research challenges reside in transforming sensor data into reliable and robust algorithms that can answer particular questions and predict the response. This requires selecting the appropriate variable(s) to measure, choosing the suitable sensing technology, and establishing an accurate reference standard when developing PLF algorithms that are reliable and adapted for rabbits. The newly developed algorithms should then be validated in different farm conditions before they can be extrapolated and implemented in commercial situations. Nevertheless, our examples also highlight some areas where PLF might be helpful in rabbit production, assisting farmers in animal care by facilitating a greater understanding of animal individual needs on farms. These PLF concepts can help bridge the gap between societal demands and those of the production sector, contributing to achieving high levels of production, efficiency, resilience and welfare in animal husbandry for the production of high-quality rabbit meat.

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REFERENCES

Adedeji O.J., Abayomi-Alli A., Arogundade O., Abayomi-Alli O., Omoyiola B.O. 2023. Deep transfer learning for classification of rabbit behaviour using publicly available datasets. *In: First International Conference on the Advancements of Artificial Intelligence in African Context (AAIAC), Arusha, Tanzania, United Republic 2023, 1-10. https://doi.org/10.1109/AAIAC60008.2023.1046547*

Adell E., Calvet S., Torres A.G., Cambra-López M. 2012. Particulate matter concentrations and emissions in rabbit farms. *World Rabbit Sci., 20: 1-11. https://doi.org/10.4995/wrs.2012.1035*

Agea I., García M.L., Argente M.J. 2021. Preliminary study of body temperature emissivity in rabbits selected for litter size residual variability. *Agriculture, 11: 604. https://doi.org/10.3390/agriculture11070604*

Bäuerl C., Collado M.C., Zuniga M., Blas E., Pérez Martínez G. 2014. Changes in cecal microbiota and mucosal gene expression revealed new aspects of epizootic rabbit enteropathy. *PLoS ONE, 9: e105707. https://doi.org/10.1371/journal.pone.0105707*

Birolo M., Trocino A., Zuffellato A., Xiccato G. 2019. Time-based feed restriction and group size in growing rabbits: effects on health status and growth performance. *Ital. J. Anim. Sci.,18: 79. https://doi.org/10.1080/1828051X.2018.1532329*

Briefer E.F., Sypherd C.C.R., Linhart P., Leliveld L.M., Padilla de La Torre M., Read E.R., Guérin C., Deiss V., Monestier C., Rasmussen J.H., Špinka M. 2022. Classification of pig calls produced from birth to slaughter according to their emotional valence and context of production. *Sci. Rep., 12: 3409. https://doi.org/10.1038/s41598-022-07174-8*

Calvet S., Cambra-López M., Estellés F., Torres A.G. 2011. Characterization of the indoor environment and gas emissions in rabbit farms. *World Rabbit Sci., 19: 49-61. https://doi.org/10.4995/wrs.2011.802*

Cambra-López M., Aarnink A.J., Zhao Y., Calvet S., Torres A.G. 2010. Airborne particulate matter from livestock production systems: a review of an air pollution problem. *Environ. Pollut., 158: 1-17. https://doi.org/10.1016/j.envpol.2009.07.011*

Cambra-López M., Blas E., Marín-García P., Zemzmi J., Ródenas L., Martínez-Paredes E., López M.C., Ramón-Moragues A., Zhao Y., Remus A., Pascual J.J. 2023. Cómo puede contribuir la ganadería de precisión a la transición hacia el alojamiento sin jaulas de la cunicultura. *In: XX Jornadas sobre Producción Animal de AIDA, AIDA-ITEA, 269.*

Cambra-López M., Ramón-Moragues A., Blas E., Marín-García P., Pascual J.J. 2024. Opportunities for precision livestock farming applications in cage-free farming. *In Proc.: European Precision Livestock Farming Conference 2024. Bolonia, Italy.*

Carpentier L., Vranken E., Berckmans D., Paeshuyse J., Norton T. 2019. Development of sound-based poultry health monitoring tool for automated sneeze detection. *Computers and electronics in agriculture, 162: 573-581. https://doi.org/10.1016/j.compag.2019.05.013*

Chen C., Zhu W., Norton T. 2021. Behaviour recognition of pigs and cattle: Journey from computer vision to deep learning. *Comput. Electron. Agric., 187: 106255. https://doi.org/10.1016/j.compag.2021.106255*

Chen Y., Niimi M., Zhang L., Tang X., Lu J., Fan J. 2023. A simple telemetry sensor system for monitoring body temperature in rabbits– a brief report. *Animals 13: 1677. https://doi.org/10.3390/ani13101677*

CIWF, Compassion in world farming. 2020. End the cage age. Why the EU must stop caging farm animals. “End the Cage Age”. *Accessible at https://www.ciwf.org.uk/*

Duan E.Z., Wang L.J., Wang H.Y., Hao H.Y., Li R.L. 2022. Remaining feed weight estimation model for health monitoring of meat rabbits based on deep convolutional neural network. *Int. J. Agric. Biol. Eng., 15: 233-240. https://doi.org/10.25165/j.ijabe.20221501.6797*

EFSA AHAW Panel (EFSA Panel on Animal Health and Welfare), 2020. Saxmose Nielsen S., Alvarez J., Bicout D.J., Calistri P., Depner K., Drewe J.A., Garin-Bastuji B., Gonzales Rojas J.L., Gortázar Schmidt C., Michel V., Miranda Chueca M.A., Roberts H.C., Sihvonen L.H., Spoolder H., Stahl K., Velarde Calvo A., Viltrop A., Buijs S., Edwards S., Candiani D., Mosbach-Schulz O., van der Stede Y., Winckler C. Scientific Opinion on the health and welfare of rabbits farmed in different production systems. *EFSA 4: 96 pp.*

European Commission. 2017. Directorate-General for Health and Food Safety, Commercial rabbit farming in the European Union - Overview report, Publications Office, 2017. *Accessible at https://data.europa.eu/doi/10.2772/62174*

European Commission. 2021. Communication from the Commission on the European Citizens’ Initiative (ECI) “End the Cage Age”. C(2021)4747. Directorate-General for Health and Food Safety, European Commission.

Exadaktylos V., Silva M., Aerts J.M., Taylor C.J., Berckmans D. 2008. Real-time recognition of sick pig cough sounds. *Comput. Electron. Agric., 63: 207-214. https://doi.org/10.1016/j.compag.2008.02.010*

García M., Gunia M., Argente M. 2021. Genetic factors of functional traits. *World Rabbit Sci., 29: 207-220. https://doi.org/10.4995/wrs.2021.13320*

Gidenne T., Fortun-Lamothe L., Huang Y., Savietto D. 2024. Pastured rabbit systems and organic certification: European union regulations and technical and economic performance in France. *World Rabbit Sci., 32: 83-97. https://doi.org/10.4995/wrs.2024.20894*

Giersberg F.M., Kemper N., Fels M. 2015. Planimetric measurement of floor space covered by fattening rabbits and breeding does in different body positions and weight classes. *Livest. Sci., 177: 142-150. https://doi.org/10.1016/j.livsci.2015.04.010*

Huneau-Salaün A., Bougeard S., Balaine L., Eono F., Le Bouquin S., Chauvin C. 2015. Husbandry factors and health conditions influencing the productivity of French rabbit farms. *World Rabbit Sci., 23: 27-37. https://doi.org/10.4995/wrs.2015.3076*

Ipek N., Van Damme L.G.W., Tuyttens F.A.M., Verwaeren J. 2023. Quantifying agonistic interactions between group-housed animals to derive social hierarchies using computer vision: a case study with commercially group-housed rabbits. *Sci. Rep., 13: 14138. https://doi.org/10.1038/s41598-023-41104-6*

Jaén-Téllez J.A., Sánchez-Guerrero M.J., Valera M., González-Redondo P. 2021. Influence of stress assessed through infrared thermography and environmental parameters on the performance of fattening rabbits. *Animals, 11: 1747. https://doi.org/10.3390/ani11061747*

Latham A.D.M., Nugent G., Warburton B. 2012. Evaluation of camera traps for monitoring European rabbits before and after control operations in Otago, New Zealand. *Wildl. Res., 39: 621-628. https://doi.org/10.1071/WR12050*

Licois D., Wyers M., Coudert P. 2005. Epizootic Rabbit Enteropathy: experimental transmission and clinical characterization. *Vet. Res., 36: 601-613. https://doi.org/10.1051/vetres:2005021*

Liu D., He D., Norton T. 2020. Automatic estimation of dairy cattle body condition score from depth image using ensemble model. *Biosyst. Eng., 194: 16-27. https://doi.org/10.1016/j.biosystemseng.2020.03.011*

Liu D., Parmiggiani A., Psota E., Fitzgerald R. and Norton T. 2023. Where's your head at? Detecting the orientation and position of pigs with rotated bounding boxes. *Comput. Electron. Agric., 212: 108099. https://doi.org/10.1016/j.compag.2023.108099*

Machado L.C., Martínez-Paredes E., Cervera C. 2019. Performance of rabbit does housed in collective pens and individual cages. *World Rabbit Sci., 27: 227-235. https://doi.org/10.4995/wrs.2019.11540*

Machado L.C., Simões J. 2024. Rabbit farming: industrial, small-scale, and organic housing systems. *In: Simões J., Monteiro J.M. (eds) Veterinary care of farm rabbits. Springer, Cham. https://doi.org/10.1007/978-3-031-44542-2_5*

Matics Z., Cullere M., Dalle Zotte A., Szendrő K., Szendrő Z., Odermatt M., Atkári T., Radnai I., Nagy I., Gerencsér Z. 2019. Effect of cage and pen housing on the live performance, carcase, and meat quality traits of growing rabbits. *Ital. J. Anim. Sci., 18: 441-449. https://doi.org/10.1080/1828051X.2018.1532329*

Martínez-Paredes E., Nicodemus N., Pascual J.J., García J. 2022. Challenges in rabbit doe feeding, including the young doe. *World Rabbit Sci., 30: 13-34. https://doi.org/10.4995/wrs.2022.15562*

Monclús R., Rödel H.G. 2008. Different forms of vigilance in response to the presence of predators and conspecifics in a group-living mammal, the European Rabbit. *Ethology, 114: 287-297. https://doi.org/10.1111/j.1439-0310.2007.01463.x*

Nan J.I., Yanling Y.I.N., Weizheng S.H.E.N., Shengli K.O.U., Baisheng D.A.I., Guowei W.A.N.G. 2022. Pig sound analysis: a measure of welfare. *Smart Agric., 4: 19.*

Negretti P., Bianconi G., Finzi A. 2007. Visual image analysis to estimate morphological and weight measurements in rabbits. *World Rabbit Sci., 15: 37-41. https://doi.org/10.4995/wrs.2007.606*

Parmiggiani A., Liu D., Psota E., Fitzgerald R., Norton T. 2023. Don't get lost in the crowd: Graph convolutional network for online animal tracking in dense groups. *Comput. Electron. Agric., 212: 108038. https://doi.org/10.1016/j.compag.2023.108038*

Pérez-Fuentes S., Muñoz-Silvestre A., Moreno-Grua E., Martínez-Paredes E., Viana D., Selva L., Villagrá A., Sanz-Tejero C., Pascual J.J., Cervera C., Corpa J.M. 2020. Effect of different housing systems (single and group penning) on the health and welfare of commercial female rabbits. *Animal, 14: 1270-1277. https://doi.org/10.1017/S1751731119003379*

Piles M., Mora M., Kyriazakis I., Tusell L., Pascual M., Sánchez J.P. 2024. Novel phenotypes of feeding and social behaviour and their relationship with individual rabbit growth and feed efficiency. *Animal, 18: 101090. https://doi.org/10.1016/j.animal.2024.101090*

Pomar C., Remus A. 2019. Precision pig feeding: a breakthrough toward sustainability. *Animal Front., 9: 52-59. https://doi.org/10.1093/af/vfz006*

Psiroukis V., Malounas I., Mylonas N., Grivakis K.E., Fountas S., Hadjigeorgiou I. 2021. Monitoring of free-range rabbits using aerial thermal imaging. *Smart Agric. Technol., 1100002. https://doi.org/10.1016/j.atech.2021.100002*

Rosell J.M., de la Fuente L.F. 2009. Culling and mortality in breeding rabbits. *Prev. Vet. Med., 88: 120-127. https://doi.org/10.1016/j.prevetmed.2008.08.003*

Rosell J.M., de la Fuente L.F. 2016. Causes of mortality in breeding rabbits. *Prev. Vet. Med., 127: 56-63. https://doi.org/10.1016/j.prevetmed.2016.03.014*

Rosell J.M., de la Fuente L.F., Badiola J.I., Perez de Rozas A., Fernández de Luco D., Arnal M.C., Casal J. X.M., Pinto de Carvalho A. 2023. Respiratory disorders of farmed rabbits: occurrence and risk factors. *World Rabbit Sci., 31: 147-161. https://doi.org/10.4995/wrs.2023.18280*

Sánchez J.P., Muñoz I., González O., Pascual M., Perucho O., Alsina P., Piles M. 2022. A computer vision system for individual tracking of group housed rabbits. *In Proc.: 12th World Congress on Genetics Applied to Livestock Production (WCGALP) Wageningen, The Netherlands, 610-613. https://doi.org/10.3920/978-90-8686-940-4_140*

Sánchez J.P., Muñoz J., Chetrit R., Pascual M., Piles M. 2024. Method: eFeederRab: A new electronic feeder to measure individual feed intake−related traits on growing rabbits raised in collective cages. *Animal - Open Space, 3: 100074 https://doi.org/10.1016/j.anopes.2024.100074*

Savietto D., Fillon V., Temple-Boyer A., Derbez F., Aymard P., Pujol S., Rodríguez A., Borne S., Simon S., Grillot M., Lhoste E., Dufils A., Drusch S. 2023. Design of a functional organic agroforestry system associating rabbits and apple trees. *Animal-Open Space, 2: 100051. https://doi.org/10.1016/j.anopes.2023.100051*

Schofield C.P., Marchant J.A., White R.P., Brandl N., Wilson M. 1999. Monitoring pig growth using a prototype imaging system. *J. Agric. Eng. Res., 72: 205-210. https://doi.org/10.1006/jaer.1998.0365*

Studd E.K., Boudreau M.R., Majchrzak Y.N., Menzies A.K., Peers M.J.L., Seguin J.L., Lavergne S.G., Boonstra R., Murray D.L., Boutin S., Humphries M.M. 2019. Use of acceleration and acoustics to classify behavior, generate time budgets, and evaluate responses to moonlight in free-ranging snowshoe hares. *Front. Ecol. Evol., 7: 154. https://doi.org/10.3389/fevo.2019.00154*

Szendrő, Zs., Dalle Zotte A. 2011. Effect of housing conditions on production and behaviour of growing meat rabbits: A review. *Livest. Sci., 137: 296-303. https://doi.org/10.1016/j.livsci.2010.11.012*

Trocino A., Xiccato G. 2006. Animal welfare in reared rabbits: a review with emphasis on housing systems. *World Rabbit Sci., 14: 77-93. https://doi.org/10.4995/wrs.2006.553*

Verga M., Luzi F., Carenzi C. 2007. Effects of husbandry and management systems on physiology and behaviour of farmed and laboratory rabbits. *Hormones Behav., 52: 122-129. https://doi.org/10.1016/j.yhbeh.2007.03.024*