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ABSTRACT

This review discusses the most relevant aspects of nutritional, reproductive and health management, the three pillars of flock efficiency, production and sustainability regarding the intensification of production in sheep and goats. In small ruminants, reproductive management is dependent on seasonality, which in turn depends on breed and latitude. Nutrition represents the major cost for flocks and greatly affects their health, the quality of their products and their environmental impact. High-yielding sheep and goats have very high requirements and dietary intake, requiring nutrient-dense diets and sophisticated nutritional management that should always consider the strong interrelationships among nutrition, immunity, health, reproduction, housing and farm management. The reproductive pattern is to a great extent assisted by out-of-season breeding, facilitating genetic improvement schemes, and more recently by advanced reproductive technologies. Heath management aims to control or eradicate economic and zoonotic diseases, ensuring animal health and welfare, food safety and low ecosystem and environmental impacts in relation to chemical residues and pathogen circulation. In highly producing systems, nutrition, genetic and hazard factors assume a complex interrelationship. Genomic and management improvement research and technological innovation are the keys to sustain sheep and goat production in the future.

Implications

The sustainability of semi-intensive and intensive production systems poses new challenges to economics, animal health and welfare, and environmental impacts, which have dynamic interrelationships. This review highlights the key points allowing effective management of high-producing sheep and goats, identifying trends for the next years.

Introduction

Small ruminant production has a significant socioeconomic and environmental role worldwide. Traditionally, small ruminants are reared under grazing systems where the more productive lands are used to feed cows, and secondarily sheep. Goats have occupied poor lands, mountainous regions and arid and semi-arid zones. These elements are mainly responsible for the worldwide differential distribution of sheep and goats and their breeds. Though they have been present in the Mediterranean Basin for millennia, the demand for milk and meat products from small ruminants increased from the second half of the 19th century, and the development of production methods towards mechanisation and genetic breed improvement allowed production intensification to support this food demand at reasonable cost. These changes were first made in developed countries, but have been disseminated worldwide in the last decades. An example is China, where industrial sheep and goat production systems gradually increase from 1990s (Bai et al., 2018) mainly for meat purposes (FAOSTAT, 2020). Also, India more than doubled the goats milk production (FAOSTAT, 2020). Currently, traditional extensive grazing systems,

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mainly using indigenous rustic breeds, co-exist, to a greater or lesser extent, with improved management systems. The sustainability of high-producing sheep and goat flocks depends on interdependent economic, environmental and social factors (Ruiz Morales et al., 2019) handled properly by efficient management.

Intensive and semi-intensive farming systems require high investment to support production under a controlled environment. An integration between nutritional, reproductive and flock health management is the key for an efficient system of production. Genetically improved breeds are reared using continuous feed cycles with high energy efficiency adequate for the production phase. Assisted reproductive technologies allow rapid genetic progress, give flocks the possibility of producing milk all year round, shortening reproductive cycles, and increasing fertility and prolificacy according to production purpose. The high dairy or meat production levels are reached by controlling biological, chemical and physical hazards, maintaining an adequate sanitary condition of the flocks. Nevertheless, the intensification of production persistently poses new challenges to prevent infectious and parasitic diseases (Perry et al., 2013), and to improve animal welfare management (EFSA AHAW Panel, 2014). These disease threats are related to environmental stressors, such as high animal density in confined grazing (Ridler, 2008) and non-grazing systems, biotic factors and host characteristics (epidemiological triad).

Small ruminants' robustness (i.e., the ability to overcome environmental constraints and maintain reproductive and productive functions) is linked to individual homeostatic (i.e., maintenance of physiological equilibrium) and homeorhetic (metabolic regulation of body tissues) responses to high production demands and outcomes (Baumgard et al., 2017). Robustness can be maintained by modulating genetic and nutritional factors (Sauvant, 2019), as well as managing all factors related to animal welfare.

The present review aims to discuss sustainable management systems at flock level leading to an efficient protein production from high-producing sheep and goats. A holistic approach is presented, ensuring an equilibrium between production, animal welfare and food security.

An overview of worldwide meat and milk production in intensive and semi-intensive systems

Worldwide, the estimated number of sheep in the averaged 2016–2018 period (last data of FAOSTAT, 2020) remained stable at around 1.2 billion heads during the last three decades, but a significant increase in milk and meat production (36% and 41% more than the 1988–1990 period, respectively) was observed. The estimated number of goats is around 1.1 billion. Between these two periods, the increase in goat population (81%) was associated with increased milk (99%) and meat yield (132%). Nevertheless, the pattern of production varies according to the different world regions (see Supplementary Table S1). Sheep farming is mainly located at 35–55° latitude north (Europe, Mediterranean Basin, Asia and Sahel region of Africa) and at 30–40° latitude south (South America, Australia and New Zealand). South Africa and India are also significant countries for rearing sheep (Fig. 1A). Goat farming mainly occurs in similar regions at 30–50° latitude north and in India. This scenario is completed in Central and South America with emphasis on Mexico and Brazil (Fig. 1B).

The dairy and meat specialisation, firstly occurring in Europe, was a consequence of significant mechanisation and intensification of flock management (i.e., nutrition, genetics, reproduction and heath) that was introduced in the 1960s and quickly expanded from the 1990s. Over the last decade, the number of sheep and goats significantly decreased in Europe, but the milk yield increased in contrast to meat production (Fig. 2A). Developed dairy industries, especially in France, Greece, Italy, Spain and to some extent Mexico, currently lead the international market. Milk of small ruminants is mainly used for processing cheese and sweets (Mexico). Cheeses, including European Protected Denomination of Origin, and cow, sheep and/or goat mixed milk cheeses, as well as yoghurts and powdered milk, are produced for local and international markets. A similar dairy pattern is observed in the American continent, while Oceania is rather specialised in meat production. Nevertheless, the number of small ruminants progressively increased in Asia and Africa during the last three decades, representing more than two-third of the worldwide meat and milk production, mainly for local markets. Overall, although the specialisation level remains low in these latter two continents, its development is to be expected due to the increased local demand and to the globalisation of the economy (Fig. 2B).

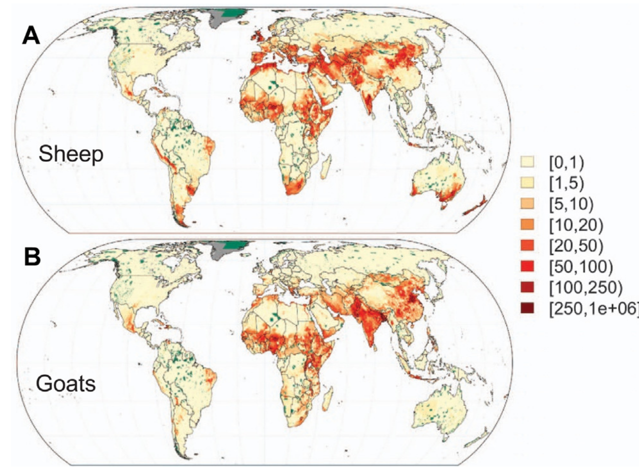

Fig. 1. Estimated worldwide distribution and density of sheep (A) and goat (B) heads per square kilometre in 2010. Adapted from Gilbert et al. (2018) according to the Gridded Livestock of the World (GLW 3). Legend: Dark grey and dark green areas correspond to unsuitable and International Union for Conservation of Nature (IUCN) protected areas, respectively.

A recent characterisation of small ruminant dairy production in worldwide industries was described by Pulina et al. (2018), using data retrieved from the Food and Agriculture Organization Corporate Statistical Database and the International Committee for Animal Recording. These authors attributed the highest levels of dairy specialisation according to the average milk yield, up 216 l/sheep and 589 l/doe, mainly in the Mediterranean basin, concluding that an increase in milk production of between 30 and 50% could be achieved by 2030 (Pulina et al., 2018). Currently, it is estimated that confined and grazing goat farms in Europe can reach 1 000 l of milk/goat per year (Ruiz Morales et al., 2019).

Nutritional management

High-yielding sheep and goats are usually reared in intensive or semi-intensive systems, often based on all-day indoor or outdoor confinement or on partial confinement with highly managed grazing, the latter being normally based on forage crops. Compared to more extensive and less productive systems, high-yielding sheep and goats require a more sophisticated nutritional management, summarised in Table 1.

Nutritional challenges of high-producing sheep and goats

High-producing sheep and goats are characterised by high milk yield, prolificacy and growth rate, depending on whether adult

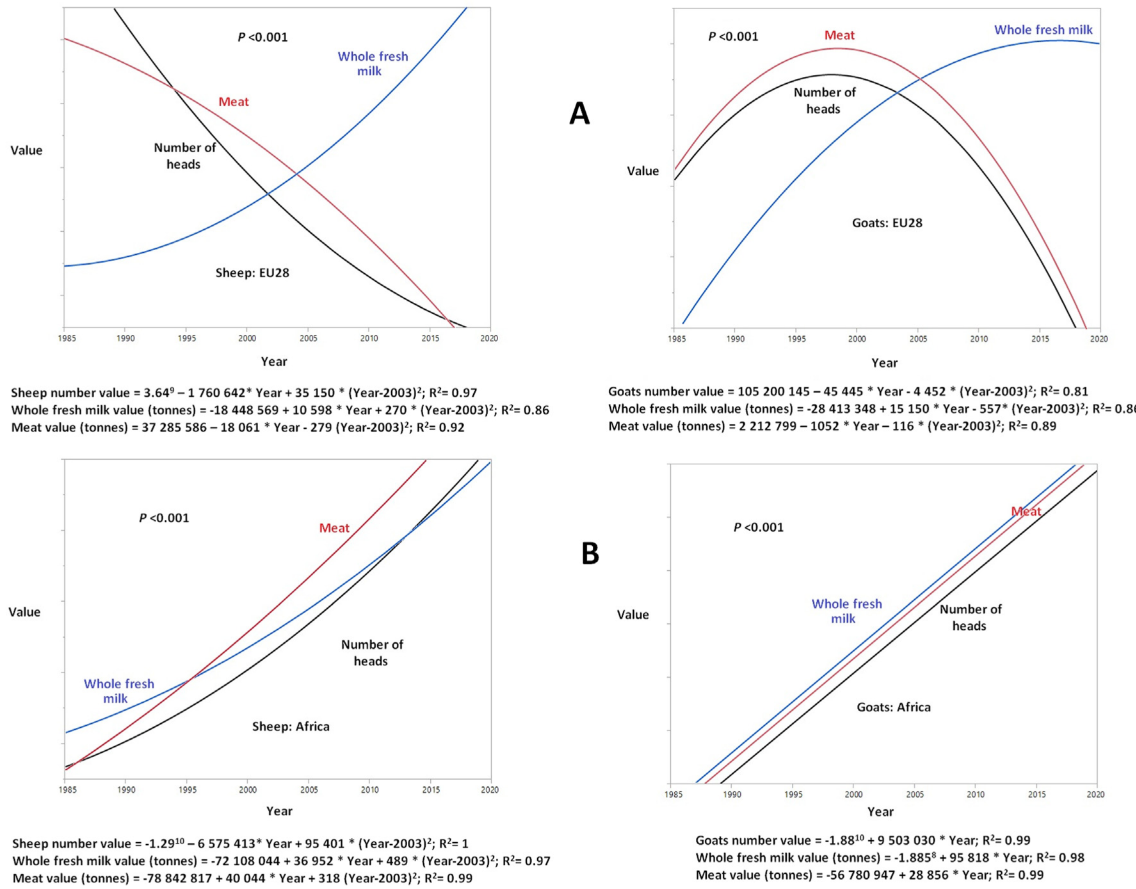

Fig. 2. Estimated values of sheep and goat numbers, whole fresh milk and meat production in Europe (A) and Africa (B). Legend: The regression curve was obtained using a quadratic regression (polynomial degree 2) between the respective values and the year, except for goats in Africa (linear Pearson correlation). The value of Y-Axis is obtained according to the value of each regression formula. Data between 2016 and 2018 were obtained from FAOSTAT (2020).

Table 1
Nutritional challenges and management solutions for high-producing sheep and goats.

Items
Nutritional challenges
– Very high requirements and thus very high feed intake and rumen passage rate, with decreased diet digestibility
– High sensitivity to the negative nutritional effects of low quality forages
– High risk of nutritional or metabolic disorders due to the use of energy dense diets
– High prolificacy and, thus, frequent high losses of body reserves during the period of transition between pregnancy and lactation
– Often very large flock size, with high numbers of animals to be monitored and high variability in their performance
– High sensitivity to meteorological conditions, because production cycles are less seasonal compared with extensive systems
Nutritional management solutions
– Integrating nutrition with health, welfare, and husbandry management, by adopting a holistic view of the flock and accounting for the many interactions among these factors
– Utilisation of forages and other fibre sources of high degradability
– Supply of properly balanced diets (and refusals' control), based on accurate and detailed feed characterisation and by using modern nutritional models, for feeding groups of animals as homogenous as possible in terms of physiological status and performance
– Monitoring of feed intake, animal behaviour, performance (milk production and composition, prolificacy, and growth rate), and nutritional disorders of the animals, by using a combination of sensor measurement technologies (to assess milk production, eating and rumination time, rumen pH, movement, and environmental conditions) and more traditional nutritional indicators (e.g. milk or blood urea, milk composition, faecal score, and body condition score)
– Collecting and interpreting technical, economic and biological animal and farm data systematically, to be able to continuously monitor the farm and animal performance
– Minimising the environmental impact of small ruminants, by avoiding nutrient spoilage and by maximising the utilisation of high quality forages and by-products
– Minimising the negative effects of adverse meteorological conditions and optimising barn environmental and comfort conditions

females or growing lambs or kids are considered. This leads to very high nutrient requirements and, consequently, high feed intake and rumen feed passage rate. Considering that the maintenance requirements are proportional to the metabolic weight of the animals, the maintenance costs per kg of BW in small ruminants are about 70–100% higher (depending on the actual BW) than in large ruminants (Cannas, 2004). The combination of high production and maintenance requirements makes the nutritional challenges of small ruminants great, often higher than those of highly productive cattle. As an example, a dairy goat of 65 kg of BW producing 5 kg of milk per day (d) with 3.5% fat (or a dairy ewe producing 3.7 kg/d of milk with 6.5% fat) has the same milk production requirements per kg of BW as those of a 650 kg dairy cow producing 50 kg/d of milk with 3.5% fat, but it also has 78% higher maintenance requirements per kg of BW than the cow. Thus, the total energy requirements per kg of BW of a goat producing 5 kg/d of milk are equivalent to those of a cow producing 61 kg/d of milk. Because the rumen feed passage rate is much higher in high-producing sheep and goats than in cattle, for proportionally equal production levels (Cannas, 2004), highly productive small ruminants utilise diets rich in slowly degraded nutrients, such as the fibre of forages, less efficiently than cattle. Compared to cattle, sheep and goats can somewhat compensate for this limitation in fibre utilisation with a better ability to utilise grains, which are ruminated more finely and thus better digested, and with a higher feed selectivity. The latter is a way for small ruminants to increase the nutrient concentration in their diet, but it also leads to potential nutritional problems, due to a likely mismatch between planned and consumed rations that the breeder has to deal with.

A particularly critical stage for sheep and goats is late pregnancy. When comparing small ruminants with cows, the combined effect of a shorter pregnancy (on average, 147 d in sheep and goats compared with 283 d of cows) and higher prolificacy (which greatly increases the ratio of litter weight at birth over the mother's BW) leads in sheep and goats to very high growth rates of the foetuses per kg of BW of the mother. In fact, in the very critical last month of pregnancy, the foetal growth rate is four times higher in small ruminants with twins and almost six times higher with triplets compared to pregnant cows, which usually have singles. This is an amazing nutritional endeavour that causes an exponential increase in nutrient requirements in a short time. In addition to the much higher pregnancy requirements, sheep and goats have higher maintenance costs per kg of BW compared to cattle, as previously discussed.

Unfortunately, during pregnancy, the capacity of sheep and goats to eat forages, with their slow degrading fibre that causes high rumen fill, does not mirror the increasing energy requirements. This is because rumen expansion and DM intake are limited by the space occupied by the uterus, and probably by subtle hormonal changes that occur in the preparation for parturition. Indeed, dietary intake actually decreases dramatically in the last 2–3 weeks of pregnancy compared to earlier pregnancy, especially in prolific or fat dams (Nielsen et al., 2015; Cannas et al., 2016).

The prolificacy of high-producing sheep and goats is usually higher in intensive than extensive systems, due to a better nutritional management during the reproductive stage and, often, as a result of the implementation of specific intensive genetic selection processes and assisted reproduction techniques. Towards the end of multiple pregnancies, excessive rapid body reserve mobilisation, due to a progressively higher negative energy balance, can induce subclinical ketosis or, less frequently, clinical ketosis (pregnancy toxaemia). Even when body condition score or BW is evaluated periodically, in modern nutritional management protocols, blood β-hydroxybutyrate and, to a lesser degree, the non-esterified fatty acids, should be the main biomarkers used to evaluate the level of ketonemia (threshold values for β-hydroxybutyrate of 0.86 mmol/l and 1.2 mmol/l for subclinical and clinical ketosis, respectively; Lacetera et al., 2001a) and thus monitor the energy balance of the animals. When comparing sheep in subclinical ketosis with ewes of the same flock with normal values, Lacetera et al. (2001a and 2001b) found that the ewes in subclinical ketosis had half of the blood immunoglobulin G concentration of those with normal status and produced with colostrum five times less immunoglobulin G, due to the combined effect of decreased colostrum production and low colostrum immunoglobulin G concentration. This striking effect of subclinical ketosis on immune defenses suggests that both the dams and the offspring suckling their colostrum could be more prone to infectious diseases. The impact of hyperketonaemia on animal health is well-documented in cows, and similar findings have been observed in high-producing sheep and goats. Dairy small ruminants suffering from hyperketonaemia are more likely to develop peri-parturient problems, immunosuppression and related infectious diseases (e.g., mastitis, metritis and lameness), and have a reduced gastrointestinal parasite resistance (Barbagianni et al., 2015a, 2015b and 2015c).

After parturition, the DM intake is usually very low and increases slowly, peaking only at 30–45 days in milk, thus initially inducing a negative energy balance. This causes, especially in high-yielding sheep and goats, fast body reserve mobilisation and increased risk of hyperketonaemia (Pichler et al., 2014; Bouvier-Muller et al., 2016) during early lactation, as often also observed in high-yielding cows. In a recent study, Pesántez-Pacheco et al. (2019) observed that the plasma β-hydroxybutyrate levels dropped during the postpartum period (52 ± 5 d) for ewes producing <0.77 l/d (1 l = 1.033 kg), but continued to rise for those producing between 0.77 and 1.12 l/d or >1.12 l/d, on average. Nevertheless, Pesántez-Pacheco et al. (2019) concluded that the impact of metabolic stress, directly measured by blood metabolites, could be maintained at acceptable levels when nutritional management was well conducted.

During lactation, the milk fat-to-protein ratio or the proportion of preformed versus *de novo* fatty acids can be used to monitor the energy balance in sheep (Pulina et al., 2006). However, more research in sheep and goats is needed to define reference values for these lipo-mobilisation indicators to the level of accuracy achieved for dairy cattle (see review of Benedet et al., 2019).

Dietary balancing and feeds for high-producing sheep and goats

Because of the high requirements of high-yielding sheep and goats, dietary formulation should be carefully carried out and monitored. Although there is a vast research literature on energy and protein requirements in sheep and goats, and some modern feeding models for these species have been published or updated in the last decade (see review of Cannas et al., 2019), none of the existing feeding systems reports optimal dietary fibre (NDF) and non-fibre carbohydrate (sugars, starch and pectin) concentrations. Thus, it becomes difficult to translate energy requirements into practical formulation of diets, considering that rumen function and microbial efficiency are markedly affected by these nutrients. This is a major limitation, especially for high-yielding sheep and goats, whose energy intake would be negatively affected by diets too rich in fibre. On the other hand, excess of sugars or starch fermented in the rumen might cause suboptimal rumen pH and associated nutritional disorders.

For sheep, preliminary guidelines for maximum acceptable dietary NDF concentration, above which DM intake is limited by rumen fill, were reported by Cannas et al. (2016), suggesting that the intake of NDF per kg of BW is much higher in ewes than in cows, both during pregnancy and lactation.

During pregnancy, the maximum acceptable NDF intake level in sheep is around 1% of BW (Nielsen et al., 2015; Cannas et al., 2016), being, for the high passage rate, much higher than that of cattle (around 0.6% of BW) and it is lower when the ewes carry twins or triplets compared to singles. This threshold in intake level leads to a maximum dietary NDF concentration of approximately 40% of dietary DM for prolific animals and of 50% for single-bearing ewes (and probably goats), when the fibre sources are mostly made up of long forages (Cannas et al., 2016).

During lactation, the maximum acceptable NDF intake level ranges between 1.8% of BW, for 90 kg ewes, and 2.1% of BW, for 45 kg ewes, with maximum dietary concentrations that vary depending on BW and milk production level (Cannas et al., 2016). Probably, similar reference values could be adopted for goats.

Fibre quality and particle size of the forages can greatly affect the above mentioned values, considering that fibre quality greatly affects rumen filling and that sheep and goats can ruminate very fine particles that would escape rumination in cattle (Cannas, 2004; Araujo et al., 2008).

Another important aspect, which has not been given due to consideration by current feeding systems, is the dietary concentration of non-structural carbohydrates, especially starch. During pregnancy, dietary starch concentration should be properly managed in order to be high enough to limit marked negative energy balances but, at the same time, not so high that the risks of over fattening and acidosis increase. This implies that the diets should be formulated and fed separately for early and late pregnancy ewes. The animals should also be grouped based on their body condition score and prolificacy. Appropriate nutritional management would then require not only a systematic assessment of the body condition score in critical periods (e.g., beginning of dry period and last month of pregnancy) but also the early identification of pregnant animals and the number of foetuses they carry. These practices are the basis of modern integrated nutrition, reproduction, and management plans implemented in various parts of the world (e.g., Belanche et al., 2019, for goats, and Sementusa Tech®, http://www.sementusa.com, for sheep and goats).

During early lactation, the utilisation of energy-rich diets (whose energy comes in general mostly from starch) is important to avoid excessively negative energy balances and sustain milk production, both in milk and meat or wool breeds (see review by Cannas et al., 2002). The maximum dietary starch concentration is set by the need to avoid rumen sub-acidosis, which in turn depends on different nutritional and managerial factors, such as quantity, quality, and particle size of the fibre, degradability of the starch source used, and number of meals. A range of starch content between 20 and 30% of the dietary DM can be suggested for early lactation.

Interestingly, during mid-lactation (after the end of the period of negative energy balance), high-yielding ewes and goats appear to respond differently to starchy diets, and to have a different nutrient partitioning towards milk or body reserves. In particular, dairy goats take advantage of high-starch diets (above 20% of DM) in mid-lactation, whereas ewes in this period benefit from low-starch diets (10–15% of dietary DM). For ewes, starch should be substituted by feeds high in energy-rich nutrients that do not stimulate the action of insulin, to which they are very sensitive, such as fats and highly digestible fibre (rich sources of which are soy hulls, beet pulps, horticultural residues or green forages in early phenological stages; Cannas et al., 2002). Research carried out to explain this difference between sheep and goats, when starch-rich diets are used during mid-lactation, suggests that in ewes, the hormonal profile is more directed towards the partitioning of dietary energy in favour of body reserve accumulation, rather than milk production, whereas in goats, the hormonal status at this time is directed towards the partitioning of energy in favour of milk production (Cannas et al., 2013; Lunesu, 2016).

Once the carbohydrates sources and concentrations are defined, the diets should be optimised with protein sources with appropriate biological value and degradability. As in dairy cows, milk urea concentration is a helpful nutritional indicator to optimise the relationship between dietary protein and energy in sheep (Giovanetti et al., 2019) and goats (Rapetti et al., 2014).

Reproductive management

Sheep and goats from tropical latitudes are non-seasonal or display a weak seasonality of reproduction (Chemineau, 1986; Mahieu et al., 1989). In contrast, sheep and goats from subtropical and temperate latitudes present a seasonal pattern of reproduction, which ensures that the offspring are born when pasture availability is optimum, during late winter and spring in moderate to high latitudes. As a result of a refractoriness to long days (Karsch et al., 1986), ewes and goats begin to ovulate in late summer or early autumn, and become anoestric in the late winter or early spring. Rams and bucks reduce their libido and spermatogenic activity at roughly the same season. This results in a seasonal lambing/kidding, a seasonal pattern of milk and meat production and a seasonal price distribution. The induction of 'out-of-season' oestrous cycles was initiated in the 1970s, to enable spring mating and therefore autumn births, providing meat and milk for the winter markets. This pioneering work involved either the administration of exogenous hormones such as progestagens and equine chorionic gonadotrophin (**eCG**) or melatonin, or control of lighting and exposure to the male.

The use of progestagens and eCG allowed the increased use of artificial insemination (**AI**) in these species, and other advanced reproductive technologies (**aRTs**) (Table 2), especially the development of multiple ovulation and embryo transfer programmes. The advances reported for *in vivo* and *ex-situ* embryo production – *in vitro* maturation, *in vitro* culture and *in vitro* fertilisation – constitute valuable tools for the genetic improvement of flocks, although they are not universally applied in small ruminants. In the last few years, the safety of using hormones in animal production and the usual surgical procedures involved in these aRTs have been questioned in a context of adequate standards of animal welfare, sustainable livestock production and food security. Thus, the use of minimally invasive methods, the exploration of new therapies based on endogenous hormones naturally produced by the animals, or the activation of rams and bucks in spring as a tool to stimulate ewes and does, are conditioning the future of aRT in small ruminants.

Artificial insemination

As an alternative to the traditional progestagen synchronisation, AI after detecting natural oestrus induced by the ram effect may be an option for hormone-free management systems. Mayorga et al. (2019) obtained a fertility rate close to 50% in Sarda ewes following this procedure (introduction of vasectomized rams and AI 24 h after oestrus detection), although the synchronisation was not as compact as with conventional hormonal treatments, and it required additional labour for oestrus detection and AI. In goats, Yotov et al. (2016) inseminated Bulgarian White dairy goats after natural oestrus detected by a teaser buck, with frozen semen, with or without gonadotropin-releasing hormone administration, achieving fertility rates ranging between 37 and 48%. However, none of these techniques allowed attainment of the high fertility rates (higher than 60%) obtained with classical progestagen-eCG treatments and AI with liquid (ewes) or deep-frozen (goats) semen (in goats: Furstoss et al., 2015). The most recent hormone-free protocols for the control of reproduction and AI in goats have been reviewed by Lopez-Sebastian et al. (2014) and Pellicer-Rubio et al. (2019).

Due to the low pregnancy rates recorded when frozen semen is used in ewes, laparoscopic intrauterine insemination is widely utilised, since fertility to cryopreserved sperm is normally improved by this route. However, laparoscopic intrauterine insemination requires veterinary expertise, implies animal welfare concerns, and requires more equipment and labour than cervical insemination (Casali et al., 2017).

Ovum pickup and embryo collection and transfer

Oocyte recovery from the oviduct and embryo collection and transfer techniques in small ruminants involve surgical procedures, which are carried out under general anaesthesia, or are even performed postmortem. During the 1980s and 1990s, non-surgical laparoscopic techniques were developed for repeated endoscopic ovum pickup in sheep, and less-invasive collection of embryos based on only three punctures with a trocar in the abdominal wall, with a three-way probe, were tested in sheep and goats. Recently, Wieczorek et al. (2020) presented a laparoscopic technique to collect oocytes, allowing the harvest of a number of cells suitable for *in vitro* culture and useful for *in vitro* maturation and *in vitro* fertilisation. These methods allow for fast and effective conduct of the operation in a living donor with minimal invasiveness, while preserving the excellent condition of the animals.

Fonseca et al. (2016) reviewed the state of the art of non-surgical embryo recovery and transfer procedures in sheep and goats, concluding that both techniques show acceptable and promising success, and that subsequent progress in the non-invasive embryo procedures in these species will permit their extensive application, as is the case in cattle. It is even likely, that in a short time, surgical embryo procedures in small ruminants will be unacceptable.

Genetic selection for reproductive traits

Two approaches through genetic selection to improve the profitability of sheep and goat farms have been developed during the last years, based on the existence of heritability of two main reproductive traits. The first approach is improving ovulation rate and litter size in sheep, which is the main factor for economic profitability in meat sheep farms. This was initiated by the identification of several mutated genes of the transforming growth factor-beta superfamily, such as the Booroola fecundity gene or bone morphogenetic protein (**BMP**) R1B, FecX or BMP15, and FecG or GDF9 (review: Gootwine, 2020). The second approach correlates a polymorphism of the melatonin gene receptor a1 (MTNR1A) with a reduction of seasonality in sheep.

Some animals exhibit a mutation in the BMP15 gene, so that a stop codon has been introduced on the X chromosome. This mutation avoids the protein encoded by the gen to translate normally, so that ovulation rate is modified, as was demonstrated in the Inverdale breed sheep (FecXI).

Since its discovery in the Inverdale breed, the presence of mutations of this gene in other prolific breeds has been tracked and has been identified in several breeds such as the Belclare and Cambridge, Galway, Lacaune, Hanna, Rasa Aragonesa, Grivette and Olkuska, whose genes were called FecXB, FecXG, FecXL, FecXH, FecXR, FecXGr and FecX, respectively. Since this mutation is located in the X chromosome, it is associated with sex, so that ovarian follicles of homozygous ewes do not progress adequately, giving rise to sterile females. This is due to the biological functions of recombinant BMP15, which has demonstrated its capacity to promote granulosa cell processes involved in early follicle growth, while simultaneously acting to restrict follicle-stimulating hormone-induced granulosa cell differentiation (review: Moore and Shimasaki, 2005). Every mutation discovered in sheep breeds presents identical mechanisms and similar phenotypic results: in heterozygosis, a variable increase in the ovulation rate and in homozygosis, sterility (Otsuka et al., 2011), so that they were named as FecX followed by the initial of the name of the breed. For instance, in the Rasa Aragonesa breed, the FecXR gene has been included in its selection scheme with a positive effect of 0.35 additional lambs per birth, resulting in a clear improvement of flock income and cost-effectiveness.

The MTNR1A polymorphism and its link with seasonality of ovulation in sheep - identified by Pelletier et al. (2000) – is now one of the genetic factors widely studied in sheep, with promising effects on the economy of farms. This gene presents two exons divided by a long intron consisting of 8 000 bp (Carcangiu et al., 2009) and enables females to exhibit estrous activity during the anoestrous season. In the Sarda breed, a correlation between the MTNR1A genotype and reproductive response following synchronisation and AI in the spring has been demonstrated, and an allelic variant of the receptor has been related with the reproductive response to the ram effect (Mura et al., 2019). A shorter anoestrous period and more full-length cycles per year have been associated with the T allele of the MNTR1A gene in the Rasa Aragonesa sheep breed (Calvo et al., 2018), and He et al. (2019) demonstrated that polymorphisms in exon two may regulate the reproductive seasonality and litter size of Small Tail Han ewes by influencing gene expression.

Photoperiod and socio-sexual cues adapted to high-producing systems

In bucks and rams from subtropical latitudes, the breeding season lasts from mid-spring to late autumn, whereas in those from temperate latitudes, it lasts from early autumn to late winter. This seasonality is controlled by the variations in photoperiod, which has been used to induce the sexual activity of males and females in spring (Chemineau et al., 1992). The introduction of a male into a group of seasonally anoestrous females stimulates ovulations within the first 4 days after joining. This phenomenon is known as the 'male effect'. However, in strongly seasonal breeds, the

Table 2
Summary of the assisted reproductive technologies available for small ruminants (S or G indicate only sheep or goats, respectively).

			Multiple ovulation and embryo transfer *In vitro* production of embryos			
Oestrous induction and synchronisation	Artificial insemination	Semen collection and cryopreservation	Superovulation	Oocyte collection (ovum pickup)	Embryo collection, cryopreservation and transfer	*In vitro* techniques
- Progestegerone (CIDR)	Cervical (S)	Artificial vagina	FSH	Surgical	Surgical	- Oocyte maturation (IVM)
- Progestagens (sponges)	Transcervical	Electroejaculation	eCG	Laparoscopy	Laparoscopy	- Oocyte fertilisation (IVF)
- Prostaglandin F2α	Intrauterine (laparoscopy) (S)	Frozen semen		Postmortem	Embryo freezing Vitrification	- Oocyte and embryo culture (IVC)
- Combination (eCG, GnRH)		Fresh semen			Embryo sexing	-Intracitoplasmatic injection (ICSI)
-Melatonin (implants)		Sexed sperm			Cloning Transgenic Nuclear transfer	

CIDR = Controlled internal drug release; FSH = Follicle-stimulating hormone; eCG = Equine chorionic gonadotrophin; GnRH = Gonadotropin-releasing hormone; IVM = *In vitro* maturation; IVF = *In vitro* fertilisation; IVC = *In vitro* culture.

response of females is low or null when the male effect is performed during mid-anoestrus, partly because of the weak sexual behaviour displayed by males which are also in their rest season (Delgadillo et al., 2002). This low response of females is dramatically improved by the use of males rendered sexually active during the rest season by previous exposure to extra light in open barns. Indeed, in bucks from subtropical, Mediterranean and temperate latitudes, exposure of bucks to 2 months of artificial long days (16 h of light/day) in autumn and winter followed by natural photoperiod increases the plasma testosterone concentrations and improves their sexual behaviour about 6–8 weeks after the end of the long days; this intense sexual behaviour lasts for about 8–10 weeks (Delgadillo et al., 2002). Similarly, in rams from Mediterranean latitudes, exposure of rams to 2 months of long days in winter increases plasma testosterone concentrations and improves their sexual behaviour (Abecia et al., 2017). These data indicate that the photoperiodic treatments are a reliable tool to stimulate the endocrine response and sexual behaviour of males from different latitudes during the sexual rest period. These sexually active males are then more efficient than the sexually inactive ones to induce sexual activity in seasonally anoestrous females. In fact, most goats joined during the seasonal anoestrous with sexually active males ovulated (>85%) and became pregnant (>74%), whereas a very low proportion of them did so when joined with sexually inactive bucks (<7%; Delgadillo and Vélez, 2010). Similarly, in sheep, the proportion of pregnant ewes was higher when joined with sexually active rams (100%), than those joined with sexually inactive ones (78%) (Abecia et al., 2018). Regarding puberty, autumn-born ewe lambs housed with vasectomized rams, and rendered sexually active by exposure to 2 months of artificial long days, initiated their ovulatory activity at 27 weeks of age, whereas this occurred at 39 weeks of age in ewe lambs housed with non-activated rams (Abecia et al., 2016). In Alpine goats in France, prepubertal does exposed to sexually active males reached puberty 6 weeks earlier than prepubertal females exposed to castrated and sexually inactive males or isolated females (Chasles et al., 2019). These data indicate that the males rendered sexually active by previous extra light are very efficient to stimulate the reproductive activity of goats and ewes during the seasonal anoestrous period, and the prepubertal period of the female replacements. Thus, this cheap and simple treatment works in different breeds of sheep and goats kept in different latitudes, allowing the control of reproduction in a sustainable way by avoiding the use of exogenous hormones.

The permanent presence of bucks and rams displaying intense (breeding season) and weak (sexual rest) sexual behaviour during the year does not prevent the seasonal anovulation in goats or ewes, respectively. By contrast, the light-treated sexually active bucks and rams did so, allowing most females to ovulate during the seasonal anovulation period. Indeed, the continuous presence of light-treated sexually active bucks allows the majority of goats (86%) to ovulate continuously during the seasonal anoestrus, compared with those kept in the presence of control bucks which were sexually inactive or without bucks at all, which all stop ovulating (Delgadillo et al., 2014). Similarly, under Mediterranean latitudes, most ewes ovulate (75%) when kept in permanent presence of sexually active rams compared with those kept with sexually inactive ones (47%; Abecia et al., 2015). These data indicate that the continuous presence of sexually active males prevents seasonal anoestrous, allowing most females ovulate all the year round.

Thus, the use of sexually active males may be very useful to control the reproduction of sheep and goats in confined and semi-extensive management systems (Table 3). This strategy is sustainable, environmentally friendly, easy to apply, and gives a better image of animal production than the hormonal treatments for out-of-season breeding.

Health management plans

High-yielding sheep and goat production is highly dependent on genetics, nutrition, husbandry factors and the absence, or the adequate management, of potentially production-limiting diseases. While intensification has some advantages in providing adequate nutrition, shelter and a risk reduction for certain diseases, it is inevitably associated with husbandry and management practices that may lead to increased transmission of other pathogens, or to stress and thus increased disease susceptibility (Jaÿ and Tardy, 2019). Health management plans thus always need to include a strong focus on stress avoidance and optimising husbandry conditions. High regional variability in breeds, farming systems and disease prevalence, as well as high variability in production systems to include meat and dairy production, hinder a blanket approach to small ruminant health plans. A good health management plan is, however, essential for a thriving sheep or goat farm. Veterinarians therefore need to provide tailor-made advice to include each farm's individual circumstances. Essential factors to consider are the possible impact on welfare and production, the zoonotic potential and any possible trade implications of diseases, as well as the cost and efficacy of control measures and their potential acceptance by the farmers (Maino et al., 2012).

Table 3
Main reproductive effects of light-treated sexually activated rams and bucks on ewes and does. Photostimulated males are exposed to artificially long days (16 h light/8h dark) for 2–2.5 months and, at the end of this period, are returned to natural photoperiod conditions (reviewed by Delgadillo et al., 2020).

Effects on	Sheep	Goats
Puberty	First ovulation is advanced 12 weeks in autumn-born ewe lambs when housed with activated rams	1. Puberty of female kids is advanced 6 weeks in the presence of active bucks 2. Three-month-old female kids present puberty at 3.5–4 months of age in the presence of active bucks
Postpartum anoestrus	Postpartum ewes housed with sexually active rams in spring advance the resumption of oestrous activity after weaning during the seasonal anoestrus	The introduction of sexually active bucks at d 30 postpartum induces more than 90% of goats to ovulate
LH secretion	1. Light-treated sexually activated rams induce LH preovulatory surges in ewes in the seasonal anoestrus, when ewes are synchronised with progestagen treatment	1. LH secretion increases within 15 min after introducing activated bucks and remains elevated for 24 h, with ovulations
	2. The continuous presence of sexually active rams prevents the seasonal decrease in plasma LH concentrations in OVX + E ewes, preventing the seasonal negative feedback of estradiol on LH secretion	2. OVX + E goats exposed to sexually active bucks increase LH secretion within 15 min of exposure and remain elevated for 12 h.
Seasonality	Ewes exposed to sexually active rams exhibit a higher proportion of monthly oestrus and ovulations than ewes exposed to rams in sexual rest, and had a significantly shorter anoestrous season than ewes housed with control rams (26 vs 89 days, respectively)	86% of does ovulate from April to July when housed with activated bucks. Inactive males led to less than 15% of females ovulating during the same period.

LH = Luteinizing Hormone; OVX = Ovariectomized; E = Estrogenized.

Health schemes should therefore be designed according to individual needs, but within the framework of each region and country and adapted to the production system (Ganter, 2008). An adequate health management programme must focus on the prevention of pathological conditions rather than treatments, improving the viability of the farm and on promoting animal welfare, while also taking into consideration the feasibility and cost of proposed measures. A robust preventative character is essential to reduce the use of antimicrobials, anthelmintics and other drugs in the light of food safety and resistance issues. An important focus should also be set on potentially zoonotic diseases (Ganter 2015). In this context, the management of abortions is of particular importance. Q-fever is one example where animal health management measures such as vaccinations may, under certain circumstances, primarily be applied to protect public health (Hogerwerf et al., 2011) rather than to increase flock or herd profitability.

An individual health management plan must be established for each farm taking into account the diseases present in the area, and several parameters should be considered: production type (meat/milk/wool), breed, management system, feed resources, local climate, reproductive targets, available facilities on the farm, infections and pathological conditions present on the farm and in the region, as well as the human resources. The personality and training of the farmer and their attitude towards the implementation of the programme are also of utmost importance (Lacasta et al., 2015).

Whilst a wide range of diseases and conditions are well-known to impact yield and profitability, they may not all be relevant in each individual farm setting. Parasite management can be of prime importance in many pasture-based production systems (Voigt et al., 2016), while certain housing conditions may, for example, predispose to respiratory diseases (Navarro et al., 2019). The management or eradication of the chronic wasting diseases such as CAE/Maedi-Visna, Paratuberculosis and Caseous Lymphadenitis can also be an important part of health plans in many settings (Nagel-Alne et al., 2014). In certain geographical regions, mycoplasmal diseases such as contagious agalactia (Jaÿ and Tardy, 2019) may also be relevant, to name but a few. Adequate nutrition and nutritional management are key players in achieving high production and disease resilience, and this important topic has been covered elsewhere in this review. A veterinary health plan should thus always include nutritional monitoring, including body condition score and the monitoring of trace element status.

Good record-keeping by the farmer and the veterinarian is necessary to develop a successful health plan – fertility and lambing records, lamb and kid mortality, milk yield and composition, growth rates, diseases present and their incidence and other performance indicators need to be well recorded to allow the assessment of the situation and the evaluation of any implemented measures. In addition, postmortem examinations and laboratory tests are required to establish and identify any diseases and conditions that may be present on the farm, as well as help to identify any potential management issues (Benavides et al., 2015). Based on these facts, problems and goals can be prioritised. Any health plan also needs to undergo continuous re-assessment and should also include appropriate biosecurity measures in order to avoid the introduction of pathogens. Disease outbreaks caused by saprophytic or facultative pathogenic organisms can often be controlled by the implementation of appropriate management changes. Management is also a key element in the prevention of parasitic, infectious and nutritional diseases. Where these measures cannot prevent or control infectious diseases, vaccination programmes should be implemented (Lacasta et al., 2015). Clostridial enterotoxaemia can serve as an example where there remains a risk in unvaccinated animals and vaccination is therefore considered essential, particularly in intensively fed, high-yielding flocks. It is crucial to assess the health status of the animals before vaccination in order to achieve an optimum immune reaction, and timing vaccination correctly is also an important factor to obtain maximum protection.

As an example for a specific health plan, we have chosen one of the most relevant disorders affecting sheep and goats in intensive, primarily housed, conditions - Small Ruminant Respiratory Complex (**SRRC**), which is traditionally described as pasteurellosis, enzootic pneumonia or atypical pneumonia. This condition is currently widely referred to as Ovine Respiratory Complex in sheep but is, however, relevant to both species. We will therefore use the term SRRC. It reflects a complex disease process involving a range of host-pathogen-environment interactions, where immunological and physiological mechanisms (host) interact with multiple etiological agents including bacteria (pathogen), plus environmental factors or stressors (environment). The main bacteria involved, *Mannheimia haemolytica*, *Pasteurella multocida*, *Bibersteinia trehalosi* and *Mycoplasma* spp., are commensal organisms of the nasopharynx and tonsils of sheep and goats and it is when animals are subjected to stress or immunodeficiency that they can cause respiratory disease (Brogden et al., 1998; Zecchinon et al., 2005; Navarro et al., 2019). Environmental factors have been proven to be fundamental in the development of the disease, and the influence of climatic and husbandry factors has been widely reported (Lacasta et al., 2008; Galapero et al., 2016; Navarro et al., 2019).

A health plan aiming at SRRC must, therefore, primarily focus on these factors by improving husbandry and climatic conditions and by removing any factors negatively influencing the host immune system. A deep understanding of the environmental dynamics of livestock facilities by the veterinarian is thus essential. Measures must include improving the environmental conditions, either by improving the facilities if the animals are housed or by protecting them from inclement weather if they are kept outdoors. Any factors negatively affecting the host immune system also need to be addressed. These may include concurrent disease, stressors or nutritional imbalances. As a final step, and only if the other measures have not achieved control, vaccination programmes can be used against the main microorganisms involved.

Vaccination against SRRC is a complex process because several serotypes of the different microorganisms are involved, with very little cross-immunity. Three types of vaccines are licensed in Europe against *M. haemolytica*: inactivated whole-cell antigens, leukotoxin toxoid and cell surface antigens of the organism grown under iron-restricted conditions (Lacasta et al., 2015). Vaccines containing iron-regulated proteins confer a high degree of protection, similar to those based on leukotoxin toxoid. Further, the inclusion of five serotypes (A1, A2, A6, A7, A9) is necessary in order to obtain good efficacy due to cross-protection afforded by these serotypes (Lacasta et al., 2015). A vaccine based on iron-regulated proteins of *B. trehalosi* is also licensed for use in small ruminants, and this product also contains *M. haemolytica* strains. All licensed *P. multocida* vaccines in the EU are bacterins.

Finally, the timing of vaccination is a crucial factor for a successful programme. It has been shown that protection from SRRC is mainly conferred by neutralising antibodies IgG_2 (O'Brien and Duffus, 1987), which are poorly transferred to colostrum (less than 5%, Hodgins and Shewen, 1994). Vaccination of ewes/does therefore does not confer immunity to the lambs/kids. An initial vaccination of lambs or kids should then be performed during the first 2 weeks of life, followed by a booster dose 3–4 weeks later. A further booster dose may be required at the age of 3 months (12–14 weeks). Further booster doses should be given every 6–12 months, depending on the production type and management system, and the potential presence of risk factors for the disease (Lacasta et al., 2015).

Challenges and new insights on small ruminant research

According to Web of Science (WoS; >30 citations; 247 initial results from 'sheep or goats' keywords on this search engine on June 25, 2020), the published research in the last 5 years largely involves molecular and genomic studies. Approximately half of these studies address the epidemiology, pathogeny, immunology, and resistance mechanism pathways of infectious and parasitic pathogens. Production systems and their environmental and ecological impact were the second most published scientific area. Other relevant lines of research concern food processing, including biotic and abiotic hazards and food consumption, reproduction, nutrition and evolutionary biology. This scientific impact order reflects the current priority for research by sheep and goat industries, probably regarding public and private financial support. Based on this ranking, it seems clear that the sheep and goat research in the next years will mainly pursue the control of diseases, the impact of small ruminant production on the environment and ecosystems and biosafety of meat and milk derived food products using molecular and genomic tools (Table 4). Our findings are in agreement with those of Clark and Mora García (2017) for the dairy goat industry, reviewing the scientific literature between 1917 and 2017. These authors also consider that sustainable feed, responsive improvement of productivity, and new products and uses of the goat (and sheep) industry will be the main areas of research during the next years.

Sheep and goat nutritional research is especially relevant, since nutrition represents the major cost for high-producing flocks and greatly affects their environmental impact. In addition, considering the nutrient-dense diets required by these animals, it appears that their nutritional management should always consider the strong interrelationships among nutrition, immunity, health and farm management, and should be based on the development of technologies and nutritional indicators able to frequently monitor the health and the productive performance of the animals.

It is clear that a better knowledge of sheep and goat physiological systems (i.e. nutritional, reproductive, immunological systems), of their interactions and of their regulation by management techniques and/or by genetic approaches, is essential. This represents a huge effort for scientists, especially when dealing with the interactions between them. It is always difficult to have specialists for such interactions and this requires collaboration between scientific domains. However, this seems crucial to develop new and sustainable management techniques and systems to be used in farms, in order to prevent diseases while allowing an optimal productivity to ensure an adequate income for the farmer.

Big efforts should also be made to reduce drug use, especially for health and reproductive management, by replacing these either by natural products or by an increase in preventive management. These approaches may include, for example, plants which can reduce the intestinal parasitic load (Mravčáková et al., 2019), or a diet using pre- and/or probiotics able to stimulate the immune system, or the manipulation of inter-individual relationships to trigger reproductive activity. This is an area where innovations can be developed using a strong association between research laboratories and farmers who are at the forefront to implement these new and sustainable techniques.

The 'last but not least' area where research investment could be made for the future of sheep and goat production is the development of non-invasive or low-invasive techniques to monitor the nutritional, reproductive and health status of animals in the farm and to permit better control. Sheep and goats are generally raised in large flocks which, compared to cattle, impairs a good knowledge of each individual animal. The use of precision livestock farming technologies may facilitate the tracking of these animals to better prevent any health problem and treat it before it affects the whole flock. In the same context, the development of high-performance vaccines, adapted to local conditions, also seems absolutely essential for the future of sustainable sheep and goat livestock systems.

Conclusions

In the last six decades, significant genetic and management improvements have been made towards the intensification of sheep and goat production. Today, extensive rearing coexists with highly specialised meat and milk production systems.

Throughout the last three decades, the worldwide sheep population has stabilised while increasing milk and meat production by around 40%. During this period, the goat population and milk yield

Table 4
Main guidelines for future research to improve sustainability of sheep and goat production systems.

Items
Adaptation and environment
• Adaptation of grazing systems to environmental changes (e.g., air temperature, water availability, soil system, vegetable and animal biodiversity).
• Selecting for robustness.
• Greenhouse gas mitigation.
Nutrition
• Development of precision feeding methods, software, and equipment.
• Nutritional characterisation and effects of cost-effective unconventional feedstuffs and by-products not in competition with the utilisation by monogastrics and humans.
• Genetic improvement of forages and of harvesting techniques.
• Development of sensors and nutritional indicators for frequent animal monitoring to reduce feed wastage, nutritional imbalances, and improve welfare.
• Rumen and intestinal microbiota manipulation, and probiotics and prebiotics use.
Reproduction
• Development of non-hormonal synchronisation of ovulations.
• Improvement of cryopreservation efficiency methods.
• Identification of specific genes to regulate reproduction.
Health and welfare
• Development of novel vaccines that allow to distinguish vaccinated from infected animals (DIVA).
• Implementation of genetic markers for parasite resistance.
• Increase of lamb and kid survival.
• Reduction in antimicrobials use.
• Improving diagnostic techniques.
New farm technology
• Tracking and monitoring systems (sensor technologies).
• Surveillance cameras.
• Database records.

doubled with a more pronounced meat yield, mainly due to Asian and African regions. Nevertheless, a specialisation and intensification of production have been observed in other regions, particularly Europe, where the sheep and goat population has decreased in an inverse pattern to that of whole milk yield. This intensification of production continuously imposes new challenges in the primary industry and implies a refined management in nutritional, reproductive and health areas. Great development of new techniques of management and research regarding intensification of both sheep and goat production occurred during the last three decades. Even though individual management plans are recommended to reach specific targets, the interrelationship between them requires a holistic approach within and between farms.

Health management programmes primarily depend on adequate control and prevention of biotic and abiotic hazards at individual, flock, regional and national levels. Farmers, veterinarians, laboratories and national authorities are the main actors to maintain the incidence of diseases or chemical residues below appropriate thresholds, particularly emerging and re-emergent diseases related to national and international trade, and climate change.

Supplementary material

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Ethics statement

No experimental procedures with animals or human subjects were conducted by the authors for this paper.

Data and model availability statement

Data about number of sheep and goats, fresh milk and meat are deposited at FAOSTAT (RRID:nif-0000-30554; RRID:SCR_006914), available to public.

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Declaration of interest

No potential conflict of interest is reported by the authors.

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Transparency Declaration

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