in the R.O.K in 2012, animal manure must be directly used as fertilizer on farmland; however, as of 2013, the amount of animal manure exceeded twice the annual nutrient demand that farmland could accommodate (309,000 tons of needs vs. 680,000 tons from manure). This excessive manure is analyzed to be one of the direct causes that led to the deterioration of the overall nutrient balance in Korean farmland [6]. In 2020, the R.O.K had the highest nitrogen balance in farmlands among the Organization for Economic Co-operation and Development (OECD) member countries at 230 kg/ha, and also the highest phosphorus balance at 46 kg/ha. Particularly, the nitrogen balance increased by approximately 7.8% over the two-year period from 212 kg/ha in 2018. [7,8]

Recently, methane gas emissions from the digestive process of ruminant animals such as cattle, sheep, and goats have been highlighted in relation to climate change. In conjunction with the ammonia, nitrous oxide, and methane gas emissions from animal manure, there is a great need to reduce greenhouse gases in the animal agriculture sector. With the government's establishment of the 2050 carbon neutrality goal, the Ministry of Agriculture, Food and Rural Affairs (MAFRA) is developing various policy measures to reduce greenhouse gas emissions in the animal agriculture sector by up to 30% by 2030 [9]. To address all these challenges, a transformation towards environmentally friendly agriculture and SAA is required, along with considerations for animal disease control and the improvement of production environments.

In the R.O.K, the concept of environmentally friendly animal agriculture began to be introduced in the early 2000s. This concept ultimately aims to cultivate SAA through environmentally friendly production practices, ensuring the healthy rearing of animals to supply safe animal products. It involves fostering SAA through environmental friendliness, natural recycling systems, and animal welfare. Despite the government's efforts, there are still significant challenges in implementing environmentally friendly agriculture and SAA in the animal agriculture field, which tends to linger on fragmented and temporary policies. Therefore, the objective of this review is to establish the direction that animal agriculture should take in the climate crisis era, and to develop effective strategies for SAA tailored to the current situation in the R.O.K by examining the trends in SAA in the U.S.

1) Overview of SAA in the U.S.

The definitions of sustainable development discussed in the U.S. vary, but most encompass the concept that achieving practical sustainability requires a balance across economic, social, and environmental aspects [10]. The United States Department of Agriculture (USDA), overseeing agricultural policies in the country, defines sustainable agriculture as managing agriculture in a way that protects the environment, supports and expands natural resources, and maximizes the utilization of non-renewable resources [11]. The legal definition of sustainable agriculture refers to the establishment of an integrated system of crop and animal production methods that meets five conditions applicable in the field over the long term; 1) it meets the demand for human food and fiber; 2) it enhances the environmental quality and the foundation of natural resources that underpin agricultural economics; 3) it efficiently utilizes non-renewable resources and farm resources, integrating appropriate ecological cycles and controls; 4) it maintains the economic viability of the farm; and 5) it fulfills conditions that improve the quality of life for farmers and society as a whole [12].

Animal agriculture in the U.S. has been working towards creating a SAA system where humans, animals, and the environment can coexist through government initiatives, industry research, technological support, and individual efforts. Efforts have been made to the develop a SAA by reducing emissions like carbon, and improving factors affecting the environment such as the carbon footprint, odors, and greenhouse gases associated with animal agriculture processes for animals such as cattle and pigs.

The U.S. inherently possesses favorable conditions for SAA, including vast land areas ensuring a stable supply chain for feed, extensive barn space, the establishment of a resource recycling system through integrated farming for crop production and animal husbandry, and government support policies in the form of agricultural subsidies. Furthermore, regional universities, research institutions, private organizations, and the animal agriculture sector have established clusters, fostering a research and development system for collaborative efforts between academia and industry. This has led to active initiatives in carbon reduction and the establishment of smart farms utilizing digital technology.

The National Laboratory for Agriculture and the Environment (NLAE), a USDA sub-organization, acts as a control center for the treatment of animal manure and odor issues. It efficiently collects all relevant information on animal manure in the animal agriculture field and ensures its effective management. The laboratory is actively engaged in on-site, practical research, including reduction strategies for animal manure, technologies for animal manure treatment, and breed-specific feeding studies, aiming to find solutions for the challenges that animal agriculture faces [13].

The transition to SAA in the U.S. appears to be primarily aimed at expanding the consumption of safe animal products and securing competitiveness in overseas export markets. The export of U.S. animal products has been increasing annually, and SAA has been part of the marketing strategy to emphasize safe and environmentally friendly animal products in international consumer markets. Utilizing various media and online/offline activities, the U.S. Meat Export Federation (USMEF) promotes the safety and SAA practices of U.S. animal products [14].

2) SAA by species in the U.S.

(1) Swine

The U.S. is the second-largest pork producer in the world, with over 80,000 swine farms. According to a report from the research team at North Carolina State University [15], the U.S. pork industry has consistently increased pig productivity over the 50-year period from 1960 to 2015 while also reducing the environmental impact. Swine farms have reduced water, land, and energy use by 25.1%, 75.9%, and 7%, respectively, resulting in their carbon footprint decreasing by 7.7%. While the number of pigs harvested increased by 29%, the number of sows actually decreased by 39%. Moreover, the feed conversion rate, which represents the amount of feed needed to produce one pound of pork, has significantly decreased from 4.5 in 1960 to 2.8 in 2015 [16]. On the other hand, the average market weight of pigs showed an increase from 90 kg to 127 kg, indicating a 38% growth [17].

Most swine farms in the U.S. are clustered around regions where crops are produced. Corn and soybeans are crucial feedstuffs as they are primary sources of energy and protein. They are predominantly concentrated in the Midwest region known as the Corn Belt, which includes Illinois, Indiana, Iowa, and Minnesota, as well as in southeastern states including North Carolina and South Carolina. The Corn Belt states produce approximately three-fourths of the total pork in the U.S. [16,18].

From a geographical and crop production perspective, the U.S. swine industry benefits from feed self-sufficiency and soil restoration through nutrient cycling agriculture, facilitating a SAA system. However, the U.S. is also addressing societal concerns about MIAA. Animal welfare or consumer organizations are advocating for ongoing transformations, prompting changes in animal agriculture systems to reduce stocking density and enhance animal welfare. Additionally, the U.S. is implementing measures such as low-carbon feed adoption, feed formulation adjustments to improve feed efficiency, and the utilization of animal manure for resource and energy conversion to minimize its environmental impact.

Despite efforts toward a SAA system in the U.S. swine industry, recent inflationary impacts and record-high production costs pose challenges. Concerns over labor shortages and consumer demand slowdown further complicate the transition from the traditional economically driven swine industry to a SAA because of its anticipated costs and time. A recent quarterly economic report released by the National Pork Producers Council (NPPC) for 2023 provides insights into the challenging realities faced by the current U.S. swine industry. Feed costs account for more than 60% of the total swine production cost, and it increased by 24% compared to a year ago. Additionally, other expenses such as labor, utility, and miscellaneous costs rose by 18%. In particular, the average production cost and breakeven point have increased by 9% compared to last year, reaching a level that has risen by approximately 60% over the past three years [16]. The ongoing high production costs pose a significant challenge to the profitability of pig farming, and pig farms find it difficult to adapt to any changes without economic viability. Therefore, it can be considered the most critical issue in the transition to a SAA system.

Recently, there has been a growing national interest in animal welfare, leading to increased demand for sustainable animal products such as organic and antibiotic-free animal products. In particular, starting this year, the state of California, which is the largest consumer of pork in the U.S., has implemented a law prohibiting the sale of animal products raised in MIAA facilities. Despite strong opposition from the pork industry, including through lawsuits filed in federal courts to stop the enforcement of the law, the ban on the sale of animal products from MIAA facilities in California has been implemented after a preparation period of several years amid public sentiment.

(2) Beef cattle

The U.S. has the world's largest feed industry, primarily producing grain-fed beef for domestic consumption and export. It accounts for approximately 20% of the world's beef production, making it the largest beef producing country globally. Approximately 85% of the grazing land for beef production in the U.S., totaling 770 million acres, is land unsuitable for crop production. This land is utilized for forage production, pasture utilization, and feed and forage crop cultivation, as well as for soil restoration through animal manure, which contributes to the development of a SAA system. From 1977 to 2007, technological advancements in cattle genetics, production, and processing in the U. S. led to a 30% reduction in the number of cattle needed to produce 10 kg of beef over a span of 30 years, and the required amount of feed decreased by 19% [19]. This has allowed a reduction in the use of natural resources such as land and water, which has helped diminish the carbon footprint. The proportion of total greenhouse gas emissions in the U.S. attributed to cattle production is only 1.9% [20].

The paradigm shift towards sustainability in the U.S. beef industry began with the establishment of the U.S. Roundtable for Sustainable Beef (USRSB) in 2015. This organization is actively working to promote continuous improvement to the sustainability of the U.S. beef value chain. They have involved stakeholders at every stage of the beef industry, including around 28,000 cattle ranchers, breeders, and grain-fed beef producers, as well as participants from various sectors such as packers, meat processors, retailers, NGOs, research institutions, and related entities. As of 2018, there are 111 member organizations actively participating in the USRSB [21, 22].

The USRSB has established six core indicators to achieve its vision of a SAA with environmental soundness, social responsibility, and economic viability. The six key indicators for SAA are 1) air and greenhouse gas emissions, 2) land resources, 3) water resources, 4) employee safety and well-being, 5) animal health and well-being, and 6) efficiency and yield [22]. These indicators serve as the primary objectives for promoting sustainability throughout the entire beef supply chain. In the early stages of the organization's activities, there was a lack of motivation towards the efforts and costs associated with implementing SAA because there was a respect for the autonomy of producers and there were no enforceable obligations.

Especially from an environmental perspective, there was a lack of corresponding economic incentives for producers in terms of external pollution control and greenhouse gas reduction. However, SAA has become imperative for securing competitiveness in future beef production and distribution with the government's strong regulations and support, which are contingent on compliance, and the increasing voice of consumers regarding animal welfare and the environment. The U.S. exports approximately 1 million tons of beef annually, with a value of around 4 billion dollars per year [23].

(3) Dairy cattle

The U.S. dairy industry aims to reduce greenhouse gas emissions by 30% by 2030 and achieve carbon neutrality by 2050. Additionally, they have developed the Net Zero Initiative to optimize water use and enhance water quality for carbon zero emissions. The Innovation Center for U.S. Dairy was established in 2008 to assess and improve economic, environmental, and social sustainability throughout the entire dairy supply chain, from production to consumption. According to a sustainability report from the center, as of 2017, the U.S. dairy industry has achieved a 30% reduction in water usage, a 21% reduction in land usage, and a 19% reduction in carbon emissions to produce one gallon (3.79 liters) of milk over the past decade. Milk productivity in the U.S. is the highest globally. Currently, the annual milk production per cow is around 18,000 kg, more than double the daily average production of 4,400 kg in the 1970s. Consequently, the average carbon footprint per gallon of milk in the U.S. is maintained at a level nearly 50% lower than the world average, showcasing a remarkable achievement in sustainability [24]. The entire dairy industry, from feed production to consumption and waste disposal in animal agriculture, accounts for 2% of the total greenhouse gas (GHG) emissions in the US according to an Environmental Protection Agency (EPA) announcement in April 2021 [20].

A climate change report released by the Food and Agriculture Organization (FAO) of the United Nations and the Global Dairy Platform in 2019 investigating the GHG emissions from 2005 to 2015 revealed that, among the ten regions studied, the North American region, including the United States, stood out as the only region where both the concentration and quantity of GHG emissions decreased while overall milk production increased. While the average GHG emissions increased by 16.5%, the North American region showed a decrease of -0.5% [2, 25].

According to a report by Devine in 2021 [26], the largest animal producers in the U.S.

could achieve net-zero greenhouse gas (GHG) emissions within the next five years. The report suggests that achieving net-zero greenhouse gas emissions on animal production could result in a restoration of annual profits of over $1.9 million per farm. She conducted a study to identify four key areas within animal agriculture for achieving net-zero GHG emissions. These four areas were improving feed production and efficiency, reducing methane emissions from the digestive processes of animals, enhancing animal manure management and improving nutrient runoff, including nitrogen and phosphorus, and promoting the production and sale of renewable energy and by-products. The research focused on exploring strategies to reduce emissions in these areas while maximizing potential profits. Key applied technologies included optimizing feed, converting animal manure into fertilizers and energy, and employing biological treatment systems like biodigesters for processing food waste. However, the report asserts that while achieving net-zero GHG emissions is technically feasible, the economic aspect presents a significant challenge. Implementing these measures at the individual farm level would incur substantial costs and time. Therefore, the report emphasizes the necessity for government-level financial incentives and supportive policies to facilitate and encourage the adoption of these practices in the animal agriculture sector.

The U.S. dairy industry has organized the Dairy Sustainability Alliance, a consortium that brings together over 180 organizations linked to the value chain for environmental and sustainability initiatives within the dairy sector. This organization is actively engaged in a variety of internal and external initiatives to pursue sustainability in environmental conservation, animal welfare, and food safety, and to ensure the economic viability and growth of the dairy industry [27].

(4) Poultry

The digestive processes of poultry, including chickens, generally generate a relatively low amount of GHG compared to ruminants, which makes poultry production relatively environmentally friendly compared to other animals. However, there are still environmental impacts in the form of GHG emissions and/or issues like eutrophication throughout the production stages from feed production to rearing and waste treatment.

In particular, the layer industry has faced persistent calls for a transition towards sustainability in terms of food safety and animal welfare due to conventional cage farming practices aimed at ensuring productivity and economic viability. The state of California passed legislation prohibiting cage farming in 2008 and has been enforcing a transition to cage-free farming since 2022 after multiple amendments. This law prohibits confining animals in structures that restrict their free movement on farms and specifies a minimum space of 0.09 m^2 per animal. Subsequently, other states such as Massachusetts, Colorado, Washington, Oregon, Michigan, Utah, Nevada, and others have also begun specifying deadlines for transitioning to cage-free farming and establishing minimum space requirements. In Massachusetts, regulations are being developed to expand the minimum space to 0.138 m^2, which is larger compared to other states. According to data from the USDA, cage-free farming increased from 6% of the total layers in 2015 to 29.3% as of March 2021. There is an ongoing plan to achieve a complete transition to cage-free farming by 2025 [28].

There is also a movement away from MIAA systems in the production stage, opting for animal welfare cage systems, free-range farming, and pasture-based systems with a reduction in the use of antibiotics. Grain production for feed is moving towards a circular farming system through the recycling of soil, feed, and manure. The resource efficiency of animal manure is also being expanded through resource utilization and energy conversion to reduce GHG emissions and mitigate the odor associated with manure.

The animal welfare standards for layers in the US are distinguished based on the roles of the federal government, state governments, and private certification bodies. The federal government provides standards solely for organic farming, while state governments regulate only the forms of production. The actual detailed animal welfare certification is independently conducted by private organizations, each having its own distinct criteria for certification [29].

Private certification standards are primarily determined by factors such as the scale of the farm and whether free-range practices are employed. There are various certifications with different criteria, including those that require complete free-range practices like Animal Welfare Approved, certifications that acknowledge selective free-range practices such as Certified Humane, and certifications like Global Animal Partnership. Certification bodies also offer a variety of certifications for different practices, such as “cage-free”, “free range”, and “natural”.

3) Digital Animal Agriculture (DAA)

(1) Application technologies and case studies of DAA for SAA

In the US, key DAA technologies for SAA include hardware such as intelligent devices or automated machinery like robots, drones, thermal cameras, autonomous farm machinery, and sensors, as well as Internet of Things (IoT) devices. On the software side, there are data analytics programs, computer vision programs, big data analytics, artificial intelligence (AI), and blockchain technology.

There are examples of data collection through automated animal management and monitoring in each of the different animal agriculture sectors. The swine industry utilizes automated weight-detecting cameras, uses thermal cameras to measure temperatures and identify pregnancy through changes in body temperature, and implements health management systems using microphones or sensors to detect respiratory issues (Wikipedia website). Data collection is also achieved through sensors that are installed inside and outside of barns, and through real-time management of optimal breeding environments, including temperature, humidity, and air quality. This involves integrating automated feeding systems, health management systems, and behavior monitoring systems, analyzing the data, and supporting optimal decision-making using AI.

In the beef cattle industry, wireless radio frequency identification devices (RFID) for enhanced identification are utilized to collect specific information from individual animals for individual identification, production management, and automatic weighing. By installing smart tags on the cattle's ear or neck, the collection of behavioral and biometric data from the cattle helps support optimal animal management, including health monitoring, precise feeding, heat detection, and breeding program operations. Recently, various forms of sensors, including oral capsules and implantable sensors, are being employed to obtain more accurate data [30]. Additionally, for grazing cattle, wireless RFID devices, smart tags, and global positioning system (GPS) trackers are employed to track herd movements. Utilizing IoT sensors optimizes pasture management by tracking individual cattle within the herd for signs of health issues or anomalies.

In the dairy industry, the use of robotic milking systems for automatic milking brings about labor savings and increased productivity. Collecting relevant data allows for efficient management of milk quality. Automatic feeding systems supply optimal feed to dairy cows, and wearable sensors attached to the cow's ear or neck and bio-capsules for oral use collect biometric data, which enables remote management of the cow's health status, body temperature, pregnancy status, and more [30].

The poultry industry, including poultry farming, employs various technologies such as automatic feeding systems, automated environmental management systems inside and outside the barn, real-time monitoring systems using surveillance cameras, and health management systems utilizing sensors. The most promising aspects of digital animal agriculture include biometric and biological sensors, big data, artificial intelligence, and blockchain technology. Through sensors, animal producers can collect real-time data on the health and welfare of animals, enabling the development of proactive management strategies for sustainable and safe animal agriculture.

Furthermore, big data analysis using AI can transform the data provided by sensors into meaningful and actionable strategies. Additionally, leveraging blockchain technology in the animal agriculture industry can enhance transparency and traceability, increasing consumer trust and improving food safety [31].

The biometric and bio sensors discussed above play a role in monitoring and providing information on the behavior and physiological aspects of the animals, which can be classified into non-invasive and invasive types. Non-invasive sensors include surveillance cameras, microphones, sensors in automatic feeding systems, weight measurement sensors, GPS, animal activity sensors based on microelectromechanical systems, thermal infrared image sensors, heart rate monitoring sensors, and face detection monitoring sensors, which are installed outside the barn. Invasive sensors include RFID sensors used in oral capsules, skin grafts, and ear tags [31].

A prominent example of invasive sensor usage is to insert sensors into the rumen of the cows or cattle to monitor their internal physiological information such as health and body temperature. Facial detection monitoring sensors use machine learning algorithms to detect facial features of animals or monitor changes in emotional states, which is utilized for animal welfare monitoring and early detection of diseases. Thermal infrared image sensors detect the temperature of various body parts, providing information on activity status, diseases, and environmental stress. This sensor, when integrated with various applications, is effective in detecting inflammatory diseases in animals. It can also monitor conditions such as mastitis in lactating cows, tail biting-induced chronic pain in pigs, and fever states [30].

The information collected in the animal agriculture sector is divided into two categories: animal-centric information and environment-centric information. For accurate management and decision-making, both types of information need to be collected simultaneously. The information collected through these various sensors undergoes big data analysis, machine learning, and deep learning processes using specialized algorithms. AI and blockchain are employed for separate data processing stages, ultimately providing valuable insights and decision support. For example, data collected through biometric sensors can be combined with big data analysis, AI and bioinformatics technology, and applied to optimize breeding programs for layers [32].

Big data analysis is the process of extracting meaningful results from vast amounts of information and diverse types of data through analysis programs. Exploratory modeling involves analyzing past data to understand the potential impact, while predictive modeling analyzes data based on specific criteria to forecast future occurrences. Through this data modeling process, big data can be utilized to enhance an animal's production capacity, productivity, and welfare. Furthermore, it can be employed to integrate the value chain of production, distribution, and consumption related to animals or establish networks with consumers.

Blockchain utilizes unique identification information for each farm and animal producer, providing distributed, transparent, and immutable information throughout the entire process from production to distribution and consumption. This is employed to ensure quality management, traceability, and transaction transparency in the animal agriculture sector. In the future, blockchain technology could prove valuable in the early detection and tracking of animal diseases such as swine flu, foot-and-mouth disease, mad cow disease, and avian influenza.

(2) Trends and future prospects of DAA for SAA

The California-based startup, Blue River Technology, utilizes intelligent devices and AI algorithms to identify weeds and precisely apply herbicides only to the weeds. This innovative approach has significantly reduced herbicide usage while increasing crop yields [33].

Carbon Robotics, a company based in Seattle, employs lasers and AI to analyze images transmitted from high-resolution cameras. This system distinguishes between weeds and crops, using highly precise lasers to remove only the weeds. This physical weed control method does not use chemicals, and provides a groundbreaking solution for practicing organic and sustainable agriculture [34].

The AI precision technology offered by Soma Detect, based in New York, supports dairy farmers in producing high-quality dairy products. Soma Detect utilizes an AI system with automated optical sensor technology and deep learning algorithms to analyze the milk quality and the health status of cows in real-time during the milking process. Through this, the system detects diseases and nutritional conditions in cattle. As a result, it allows cows to maintain optimal health, leading to the prevention of animal diseases and an increase in milk production [35].

Farmwave, a software company based in Georgia, utilizes AI systems with machine learning algorithms and an camera system attached to a combine to monitor harvest operations in real-time. When a problem arises, it responds immediately, minimizing crop losses during harvesting and maximizing profits. For instance, Farmwave monitors the loss of beans during harvesting and adjusts the combine's fan speed to reduce the loss of beans [36].

The Korean agricultural machinery manufacturing company TYM (Dongyang Industrial) operates its distribution network, including intelligent tractors, from its U.S. headquarters in North Carolina [37]. The T130 tractor developed by TYM features a wireless vehicle internet service known as telematics and cutting-edge autonomous driving capabilities. It is optimized for farming operations in the vast and large-scale agricultural conditions of the U.S., enhancing productivity and minimizing resource waste.

Farmers Business Network (FBN), headquartered in California, provides a digital platform for agricultural data. This platform supports farmers in optimizing their agricultural management through various services, including data analysis, procurement and utilization of agricultural supplies, financial and insurance consultations, and distribution network management. Additionally, FBN utilizes AI and machine learning to analyze data related to crop yields, soil conditions, and climate patterns, providing an optimal decision-making system [38]. Through this platform, farmers can obtain and analyze data tailored for optimal agricultural management, thus enhancing their competitiveness in agriculture.

Fertile-eyez, developed by Verility based in Indiana, is a smartphone application-based solution and the first AI-based birthing support system in the animal agriculture sector. This solution utilizes AI image recognition to quickly analyze cell morphology, providing information on sperm quality such as the shape, motility, and concentration of sperm, as well as detecting ovulation in females. Through this service, farmers can easily analyze the sperm state and ovulation of animals on the farm [39]. Using this analysis information, improvements in pregnancy rates can be achieved, leading to enhanced productivity on the farm.

The Korean digital animal startup, uLikeKorea, was contracted to supply an oral IoT bio-capsule to the Bella Holstein Farm in Colorado last year. When administered through the cow's mouth, this system adheres to the rumen of the cow, providing accurate biological information. Through artificial intelligence analysis, it offers real-time health management services on an animal healthcare platform [40]. Unlike traditional methods of collecting biological information from external parts of cattle such as the ears, neck, or legs, this method allows for a more accurate and stable system operation by collecting information from within the body.

As digital transformation based on networks and knowledge information accelerates across society, the world DAA market size is also rapidly increasing. The digitization of animals is emerging as an optimal alternative to overcome the crises in the agriculture and animal agriculture sectors, creating new added value and opportunities. The global market size of digital agriculture was estimated at $19 billion in 2022, and it is expected to grow at an annual rate of 10.1%, reaching approximately $49.5 billion by 2032 [41]. With the projected 2.6-fold growth in the global digital agriculture market over the next decade, this trend is expected to continue.

The U.S. stands as the largest market for digital agriculture, supported by substantial investments aimed at building a stable food ecosystem for the future. The Asia-Pacific region, though smaller in scale, is anticipated to be the fastest-growing market. Additionally, the global animal digital monitoring market is estimated to be $5.2 billion in 2022, projected to reach $6 billion in 2023, and is expected to expand at a compound annual growth rate of 17.99% from 2023 to 2030 [42]. With the rapid increase in global animal populations and the COVID-19 pandemic leading to a global risk-averse attitude toward animal viruses, real-time animal monitoring systems are experiencing significant growth. The adoption of these systems is increasing, driven by their effectiveness in real-time prevention of animal diseases and the containment of their spread, and by their substantial cost savings in animal management. Meanwhile, global IT companies like Google and agricultural firms such as Monsanto are aggressively acquiring and significantly expanding their investments in startups related to digital agriculture.

DAA is spreading globally, with many companies and startups developing and promoting innovative products. However, there are various constraints and limitations despite the ongoing development. Technologies associated with DAA such as precision animal agriculture, big data, artificial intelligence, and blockchain, are still in the early stages of application on farms. For universal adoption across farms, advanced technological development is required, along with overcoming constraints related to time, space, and cost. The core technologies driving DAA, such as AI and blockchain, are evolving in the initial stages and face validation challenges when scaled up.

Furthermore, DAA technologies require integrated platforms that can classify and analyze vast amounts of data for specific variables, supporting predictive decision-making. This integrated platform demands the establishment of networks for sharing, facilitating big data collection and analysis, and implementing AI through algorithms. During this process, addressing issues related to data privacy, security, and integration remains a challenge. As DAA undergoes numerous trials and evolves in the animal agriculture field, connecting all of the resources in the animal agriculture sector will become possible, leading to the development of an integrated platform. DAA is likely to spread more rapidly once it is combined with innovations in digital solutions for animal agriculture to address food security, environmental concerns, and food safety, and meet consumer demands.

4) The societal demand for sustainable animal products in the U.S.

U.S. consumers have a high preference for safe animal products and place significant importance on environmental and social values in their purchasing decisions. With an increasing concern for animal welfare, there is a strong aversion to unethical production environments and practices that violate animal rights, particularly towards cage farming.

According to a survey commissioned by World Animal Protection and Crate-Free Illinois and conducted by the Harris Poll in 2021 with more than 2,000 U.S. consumers, over 73% of respondents expressed that they would not accept the practice of confining pregnant sows in gestation stalls and would choose not to purchase products that used this practice. Additionally, 56% of respondents stated that they would prefer pork produced in a way that eliminates the practice of tail docking piglets [43].

According to an online survey conducted by Acosta, a U.S. market research firm, in 2021, environmental and sustainability factors are driving consumer purchasing decisions. 65% of consumers considered sustainability as an important factor when making purchasing decisions. Therefore, in the current U.S. retail industry, sustainability is presented as a top priority, with some retailers specializing in and promoting products with sustainable features. Additionally, certification is implemented to ensure that only sustainable products are sold. In particular, 75% of the millennial generation considers sustainability as a crucial factor in making purchase decisions, indicating a higher purchasing intensity among young consumers. This trend is expected to strengthen further in the future. Furthermore, 85% of consumers who purchase eco-friendly products stated that they will continue to buy such products in the future, indicating a high level of loyalty to environmentally friendly items. In a survey regarding consumers' willingness to pay an additional amount for sustainable animal products, 74% of respondents expressed a willingness to pay more for sustainable meat, while 78% were willing to do the same for dairy products [44].

In the U.S. consumer market, sustainable animal products have been successful in securing a stable and loyal customer base. The retail industry has responded by specializing in the sale of products associated with sustainable animal farming, ranging from stores exclusively offering organic products to various other formats that highlight and sell sustainable animal products. According to on-site surveys of retail stores, the retail prices for various sustainable animal products such as organic animal products, processed items, free-range eggs, and grass-fed processed products are generally sold at prices that are around 20% to 50% higher than regular products. Some products sold by Whole Foods Market, an organic-focused retail store, are priced at more than 100% higher than regular products. Despite the higher prices, they have managed to secure a stable base of loyal customers.

Many global investment institutions, including the Government Pension Fund Global in Norway, are setting 'ESG management' as a strong investment condition. In addition, global companies in the food and retail industries, such as Unilever and Nestlé, are actively participating in carbon neutrality efforts. Multinational companies including hotels are adopting a policy of using sustainable raw materials as a key means of achieving carbon neutrality [45]. In the U.S., retail and distribution companies such as Lidl US, The Giant Co., and Sprouts, as well as processing companies like Bumble Bee and Kellogg Co., are prioritizing sustainability by establishing certification and distribution systems centered around their brands. The social awareness of various sustainable products, including sustainable animal products, is expected to continue spreading across the food, distribution, and hospitality industries, leading to a sustained increase in demand.

5) Activation of SAA led by private organizations.

Various private organizations are active in promoting SAA in the U.S., including the National Sustainable Agriculture Coalition (NSAC), SAA associations by species, consumer groups, environmental organizations, and the USMEF. Each animal agriculture sector has specific associations and cooperatives to demonstrate and disseminate various SAA specifications and management techniques on the ground. These organizations play a key role in leading government support policies in the field of SAA.

Consumer organizations actively monitor the production systems of agricultural and meat products from the perspective of consumer health rights. They aim to ensure safer and economically viable agricultural and meat production systems. Moreover, these organizations advocate for SAA practices that are aligned with consumer consumption patterns. Environmental organizations advocate for the transition to SAA as a response to various environmental pollutants and damages associated with agricultural production and animal farming. Additionally, they call for an active assessment of the implementation of major policies, urging proactive evaluation and feedback mechanisms regarding environmental impact and improvement measures.

The USMEF is a non-profit organization established for the promotion of U.S. meat exports. It was founded with the participation of domestic grain producers, animal producers, meat processors, exporters, and other agribusinesses in the U.S. The organization focuses on enhancing the international market presence of U.S. meat products and providing support to domestic animal agriculture industries. This organization employs SAA as a primary means of export marketing. Through this approach, it aims to produce, process, and distribute safer meat products while contributing to global climate crisis mitigation efforts. The incorporation of sustainability into meat export products aligns with the organization's commitment to environmental responsibility and resilience. Ultimately, this organization is working to expand the societal demand for meat produced through SAA within the U.S. Simultaneously, it aims to create opportunities for the widespread adoption of SAA.

The NSAC is the largest organization leading sustainable agriculture efforts in the U.S. In response to the farm crisis in the U.S., local farmers and ranchers facing challenges on the ground have come together to form organizations supporting sustainable agriculture since the mid-1980s. They have been actively working to explore opportunities for small to medium-sized family farms. The NSAC was established in 2009 through the merger of the Sustainable Agriculture Coalition based in the Midwest and the National Campaign for Sustainable Agriculture (NCSA), formed to influence federal food policies.

This organization is a coalition of over 130 member organizations nationwide, formed with the purpose of advocating for and improving sustainable food and agriculture policies at the federal level. Headquartered in Washington, DC, it collaborates with regional grassroots organizations, conducting research, development, and advocacy for federal policies. This approach aims to expand support, education, implementation, and engagement of local farmers in sustainable agriculture.

Firstly, it collects opinions from farmers and ranchers practicing sustainable agriculture, as well as those directly involved in local farms, food-related organizations, and rural community groups. It develops policies based on this input and advocates for them at Congress and the USDA. Additionally, this organization works to promote sustainable agriculture as a strategy for small to mid-sized family farmers, who form the backbone of U.S. agriculture and rural communities, to have stable farming opportunities and ensure economic viability. This coalition functions as a collaborative effort involving a diverse range of organizations, from large national entities such as the Sierra Club and the National Farmers Union to small grassroots associations like farmer's markets and food purchasing cooperatives. Additionally, consumers, environmental activists, wildlife advocates, educational institutions, religious organizations, local community food security groups, civic activists, and rural community organizations participate and collaborate to promote sustainable agriculture. They work towards spreading sustainable agriculture, engaging with consumers, and influencing changes in federal policies.

To promote sustainable animal husbandry, efforts are focused on research, policy development, and on-field dissemination across all stages of animal management. This includes establishing a cyclical rotational grazing system, integrating crop and feed production with animal agriculture on the same farm in a cyclical farming system, creating a trust system for the consumption and distribution of safe animal products produced through SAA, reducing the use of antibiotics in animal agriculture, and implementing environmental conservation and preservation systems.

Support programs related to SAA that take into account environmental safety, the health of farmers, and animal welfare, include the Sustainable Agriculture Research and Education Program, the National Sustainable Agriculture Information Service, the Organic Agriculture Research and Extension Initiative, the Value-Added Producer Grant Program, the Farmers Market and Local Food Promotion Program, the Beginning Farmer and Rancher Development Program, and the Agricultural Conservation Easement Program under the Farm Bill (NSAC website).

In sustainable agriculture, there is an emphasis on diverse crop rotations, the use and expansion of perennial crops, and pasture-based systems to underscore its interconnectedness with SAA. Additionally, SAA provides stable nutrients through manure and liquid fertilizer, preserving the surrounding environment. It can also be a crucial component of sustainable agriculture by utilizing land unsuitable for crop production to cultivate forage crops or pasture, contributing to its widespread adoption and dissemination. To support region-based SAA, there is an emphasis on minimizing environmental impacts throughout the production, processing, and distribution stages. SAA focuses on responsible management activities that contribute to the production of safe and environmentally stable food, including the reduction of antibiotic use (NSAC website).

Summary and Conclusion

The transition of the U.S. towards SAA appears to be driven by both external goals related to addressing climate change and the primary objectives of responding to the demand for safe animal products, expanding consumption, and securing competitiveness in overseas export markets. The demand for animal welfare, organic animal products, and processed goods has been increasing in the U.S. consumer market. In response to the growing social demands for GHG reduction, minimizing environmental impacts, and environmental conservation in animal agriculture activities, there is an ongoing transition from MIAA to environmentally friendly SAA.

The annual increase in the export of U.S. animal products reflects their growing demand in international markets. The success of a marketing strategy emphasizing safe and environmentally friendly animal products underscores the need for SAA in the global animal agriculture sector. Particularly noteworthy is the fact that since the 1970s, the U.S. animal agriculture sector has consistently reduced its carbon emissions through various means, a significant achievement in the current era of climate crisis. According to research findings, the beef production system in the U.S. exhibits significantly lower carbon emissions compared to systems in other countries. Based on empirical results indicating that feeding a combination of forage and grain is more effective in reducing methane emissions than feeding forage alone, the U.S. animal agriculture sector has adjusted the feed composition ratio, which has led to a reduction of approximately 34% in methane emissions in the U.S. since 1975. A major factor in the transformation of the U.S. animal agriculture sector in terms of livestock specifications is attributed to environmentally friendly practices such as high-quality feed, heat stress reduction, improvements in reproductive ability and growth period reduction, and efforts in animal genetic enhancement [46].

The U.S. animal agriculture sector's practices have dramatically increased beef productivity while reducing the use of natural resources such as water, land, and feed. Additionally, these practices have led to a decrease in carbon emissions. Furthermore, the extensive land area of the U.S. allows for the direct production of pasture, forage, and grain feed such as corn and soybeans. The manure from animal agriculture is recycled back to the fields, creating a circular agricultural system that contributes to a sustainable and resource-efficient economy. This process has led to cost savings and increased productivity for animal producers, contributing to enhanced farm income. It has also facilitated supply and price stability in the domestic meat consumption market in the U.S. The U.S. government continues to support research aimed at reducing carbon emissions from the animal agriculture sector and encourages its transition to SAA. However, there is no apparent plan to shrink the scale of the animal agriculture sector itself [46]. The U.S. appears to support SAA as one of the measures to cope with the increasing domestic demand for meat, ensuring stable price management, and securing income stability for animal producers.

In the R.O.K, there has been a gradual spread of initiatives towards SAA, and consumers have been increasingly seeking valuable consumption by considering factors such as the environment and animal welfare. The agricultural sector in the R.O.K still lacks precise measurement and verification methods for GHG emissions, reduction amounts, and carbon sequestration, leading to situations where indirect estimations are used for predictions. The lack of scientific measurement has been pointed out as an institutional limitation in the transition to SAA [47]. Given the rapid implementation of government regulations and support policies for climate change mitigation, there is an urgent need for accurate GHG measurement methods and the establishment of standardized units. Based on accurate measurement data, it will be possible to adjust and control carbon sequestration or GHG emissions, allowing for feedback on policy measures.

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List of Abbreviations

AI: Artificial Intelligence

DAA: Digital Animal Agriculture

FBN: Farmers Business Network

GHG: Greenhouse Gas

GPS: Global Positioning System

IoT: Internet of Things

MIAA: Mega-sized intensive animal agriculture

NCSA: National Campaign for Sustainable Agriculture

NSAC: National Sustainable Agriculture Coalition

R.O.K: Republic of Korea

RFID: Radio Frequency Identification Devices

SAA: Sustainable Animal Agriculture

U.S.: United States of America

USDA: United States Department of Agriculture

USMEF: U.S. Meat Export Federation

USRSB: U.S. Roundtable for Sustainable Beef