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NEW TECHNOLOGIES. ARTIFICIAL MEAT AS A NEW SOURCE OF PROTEIN PRODUCTS IN THE NUTRITION OF MODERN PEOPLE

Lyudmyla V. Peshuk, Daria Y. Prykhodko

Oles Honchar Dnipro National University, 72, Gaharina av., 49000, Dnipro, Ukraine

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Abstract

The need for protein raw materials is steadily growing, in accordance with the increase in the population. From time immemorial, meat has been the main component of the human diet, a source of protein and the main energy component necessary for the full functioning of body processes. Artificial meat is a rapidly growing food category that has the potential to change our eating habits. Animal products are replaced by plant-based alternatives that taste and look similar to meat. The goal of such changes is to reduce global dependence on animal agriculture. Currently, there are three categories of artificial meat that differ in technology: cultured meat, modified meat, and plant-based alternative meat substitutes. Meat culture is a complex technology for reproducing the structure of livestock muscles from stem cells, which, in a suitable environment enriched with nutrients, hormones and growth factors, are capable of transformation into muscle and fat cells. Artificial meat production has already faced many hurdles, but it still has a long way to go before it becomes a commercial reality, with societal acceptance, expanded production methods, and lower costs. That is why alternative meat products made from vegetable components are more common on the artificial meat market. As substitutes for animal raw materials, manufacturers use soy, soy isolate, seitan, chickpeas, lentils, peas, algae, insects and other high-protein ingredients. In the near future, the traditional production of meat with the participation of animals is unlikely to be stopped, but the demand between consumers and the range of protein vegetable substitutes is developing rapidly. The food industry faces the task of adapting innovative technologies of artificial meat to the needs of the population, which can provide a significant impetus to the improvement of the ecological situation and the elimination of human nutritional deficits.

Keywords: artificial meat; vegetable raw materials; meat substitutes; protein; livestock; cultivation; safety.

НОВІ ТЕХНОЛОГІЇ. ШТУЧНЕ М’ЯСО, ЯК НОВЕ ДЖЕРЕЛО БІЛКОВИХ ПРОДУКТІВ У ХАРЧУВАННІ СУЧАСНОЇ ЛЮДИНИ

Людмила В. Пешук, Дар’я Ю. Приходько

Дніпровський національний університет імені О. Гончара, пр. Гагаріна, 72, 49000, м. Дніпро, Україна

Анотація

Потреба в білковій сировині неухильно зростає, відповідно до збільшення чисельності населення. М’ясо споконвіку є основною складовою людського раціону, джерелом білка та головним енергокомпонентом, необхідним для повноцінного функціонування процесів організму. Штучне м’ясо – це стрімко зростаюча категорія продуктів, яка може змінити наші харчові звички. Продукти тваринного походження замінюють рослинними альтернативами, які на смак і вигляд схожі на м’ясні. Мета таких змін – зниження глобальної залежності від тваринного сільського господарства. Сьогодні відомі три категорії штучного м’яса, які відрізняються за технологією: культивоване м’ясо, модифіковане м’ясо та альтернативні замінники м’яса на рослинній основі. Культивування м’яса є складною технологією відтворення структури м’язів худоби з стовбурових клітин, які у відповідному середовищі, збагаченому поживними речовинами, гормонами та факторами росту, здатні до трансформації у м’язові та жирові клітини. Виробництво штучного м’яса вже зіткнулося з багатьма перешкодами, проте попереду його чекає прийняття суспільством, розширення способів виробництва та зниження вартості, перш ніж воно стане комерційною реальністю. Саме тому більш розповсюдженими на ринку штучного м’яса є м’ясні альтернативні продукти з рослинних компонентів. В якості замінників тваринної сировини виробники використовують сою, соєвий ізолят, сейтан, нут, сочевицю, горох, водорості, комах та інші високобілкові інгредієнти. Найближчим часом традиційне виробництво м’яса за участю тварин навряд чи буде припинено, проте попит серед споживачів та асортимент білкових рослинних замінників стрімко розвивається. Перед харчовою індустрією стоїть завдання адаптувати новаторські технологій штучного м’яса відповідно до потреб населення, що може надати суттєвий поштовх до налагодження екологічної ситуації та ліквідації харчових дефіцитів людства.

Ключові слова: штучне м’ясо; рослинна сировина; замінники м’яса; білок; худоба; культивування; безпека.

**Corresponding author: e-mail: dasha0972310144@gmail.com*

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Introduction

Back in the 1930s, the British minister Winston Churchill proposed the idea of using meat by cultivating individual tissues in the medium, rather than growing whole animals. This can be regarded as a rudiment of cultured meat, but from the point of view of science and technology at that time, cultured meat was just a fantasy and a vision of the future. It was at the beginning of the 21st century that research into cultured meat began. Since 2002, the National Aeronautics and Space Administration (NASA) have funded research on the production of cultured turkey meat and goldfish, creating the first edible cultured turkey strips and fish fillets. In 2013, Professor Mark Post launched the world's first cultured beef hamburger after years of research, consisting of more than 10,000 muscle fibers and costing almost $330,000, when the usual one dollar [1]. Despite the high cost, the success of cultured meat technology has attracted a lot of attention from people from all walks of life, including scientists, entrepreneurs and investors. Since then, numerous companies have been founded to develop cultured meat products and have gained access to capital, fueling the explosion of the cultured meat industry [2].

Table 1

The largest consumers of meat in the world in 2019 (OECP, USDA, European Commission)

Countries	Pork		Beef		Poultry	
	kg/person	% total consumption	kg/person	% total consumption	kg/person	% total consumption
China	24.4	44.8	4.1	8.4	14.0	22.8
USA	24.0	10.1	26.3	12.4	50.1	18.7
EU	10.8	20.4	31.3	7.9	25.6	11.6
Brazil	12.8	3.5	25.2	7.6	40.3	9.7
Russia	20.6	3.8	10.1	2.4	30.6	5.1
Mexico	14.4	2.4	9.2	1.7	30.5	4.4
Japan	16.2	2.6	7.5	1.4	17.7	2.6
Vietnam	26.0	3.2	8.1	1.1	16.2	1.8
India	0.2	0.3	0.5	1.0	2.4	3.7
United Kingdom	16.0	1.4	11.4	1.1	17.7	2.3
Argentina	11.4	0.7	38.0	2.4	37.9	1.9
Korea	31.2	2.1	11.8	0.9	18.7	1.1
World	11.1		6.4		14.7	

According to the Sustainable Development Goals, which are the UN's agenda for the 21st century, nutrition takes center stage after poverty alleviation. The second of the 17 goals is aimed at "eliminating hunger, ensuring food security, improving nutrition and promoting the sustainable development of agriculture." Achieving this goal by the 2030 deadline requires radical changes in the global system of food and agricultural production. During the two decades that have passed since the beginning of the third millennium, the world's need for food has been steadily increasing against the background of an increase in the population. According to the latest data, about 821 million inhabitants of the planet (a ninth part of the population) experience a shortage of food. This means that every ninth person in the world does not receive enough nutrition to maintain a healthy and active lifestyle. In fact, hunger and malnutrition are the number one health threat worldwide, ahead of AIDS, malaria and tuberculosis [3].

Discussion of the results of the analysis

According to the method of achieving the necessary properties, healthy food products are divided into products obtained by directed in vitro and in vitro modification of raw materials. These foods include:

Products obtained as a result of natural enrichment are products obtained on the basis of agricultural raw materials (plant and animal), as a result of which the necessary ratio of target ingredients was achieved as a result of cultivation.

Products, the necessary properties of which are obtained as a result of manipulation with animals (poultry) – trophinotropins – the products of this group include, first of all, those obtained from purposefully created breeding stock, genetically modified, as well as from animals subjected to special effects in order to achieve specific characteristics clear raw materials.

Organic (ecological) products – a food product, an assortment of products made from agricultural raw materials grown in an extensive way, without the use of medicinal, chemical and similar growth stimulants, as well as pesticides and herbicides [4].

The above classes of products refer to food products obtained as a result of in vitro modification. Changes in the composition and properties of meat raw materials after animal slaughter (in vitro) allow obtaining:

Artificially enriched products are food products, in the recipes of which additives were introduced at the stage of preparation, which led to the achievement of the required ratio of target ingredients. According to the general orientation, healthy food products are divided into food products that provide:

Functional nutrition is a modified food product, an assortment of products that contains nutrients in the amount and required ratio, which helps to improve individual functions of the body, and also prevents the occurrence of diseases [5].

The growth of meat production on a global scale will further exacerbate the problems associated with it, which include the inefficient use of energy and labor resources, feed and water in the food chain per unit of animal protein production. In addition, the burden on the environment is increasing. Meat is one of the most important food resources with high nutrition and protein content, the consumption of which is an integral part of life for most people. Breeding, raising and slaughtering animals requires many resources, which are insufficient to meet the demand for meat. By 2050, the population is expected to grow to 10 billion people, and it will be possible to feed them with meat only if production increases by 76%. Therefore, it will be impossible to provide people's diets with high-quality animal protein obtained exclusively through the use of traditional meat production, while not ultimately destroying the ecology [6].

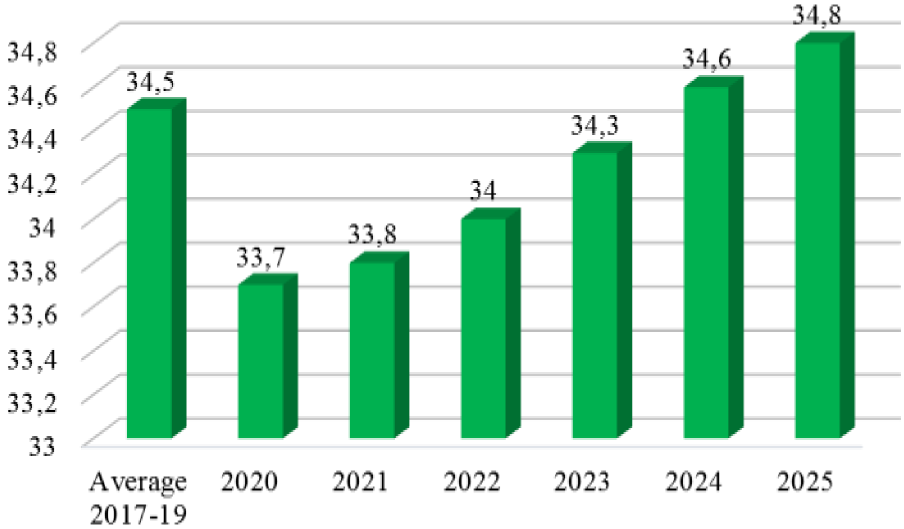

Fig.1. Meat consumption in the world, kg/person (FAO, OECP)

It is cattle, according to the publications of many scientists from different countries of the world, that is one of the main polluters of the environment. In countries with developed animal husbandry, the amount of pollution even exceeds all the greenhouse gases produced by cars, airplanes and power plants. Cattle release large quantities of methane into the atmosphere, which is 25 times more harmful than carbon dioxide, the excess of which is the main cause of global warming. In addition to pollution, raising animals requires large amounts of clean water. To obtain one kilogram of red meat, an animal needs 3,000 liters of water, the shortage of which currently affects about 700 million people around the world. Looking at this, humanity must find alternative protein components of the diet, meat substitutes, implement innovative solutions to overcome global malnutrition and solve the problems associated with the meat industry [7]. Artificial meat is a rapidly growing food category that has the potential to change our eating habits. Animal products are replaced by plant-based alternatives that taste and look similar to meat. The goal of such changes is to reduce global dependence on animal agriculture.

Currently, meat cultivation technologies are at the stage of development. Researchers check its food safety and quality, try to reduce the cost of the growing process, while improving the taste of the product as much as possible and speeding up its production. It is assumed that by 2035 the price of artificial meat will be lower than that of natural meat, which will increase its demand among the population. Over time, the share of consumption of artificial meat before natural meat may reach 50 % [8].

Such popularity of alternative sources of protein is due, first of all, to environmental factors, so most consumers of artificial meat made a conscious choice in favor of ecology. A special tendency towards the desire to reduce the "carbon footprint" is observed among young people (age category 18–24). In the US, they make up almost 40 % of all artificial meat consumers. According to an online survey conducted by Wenjuanxing, among 1,100 respondents, 70 % were ready to try artificial meat, 58 % agreed to buy it, 34 % of participants were completely ready to replace the consumption of natural meat, 16% were ready to switch to artificial meat, even if it costs more than natural meat. Only 8% of respondents are not ready to even try cultured meat, 13% do not want to buy and include it in their daily diet, and 25% of people are currently not ready to give up natural raw materials in favor of artificial ones [9].

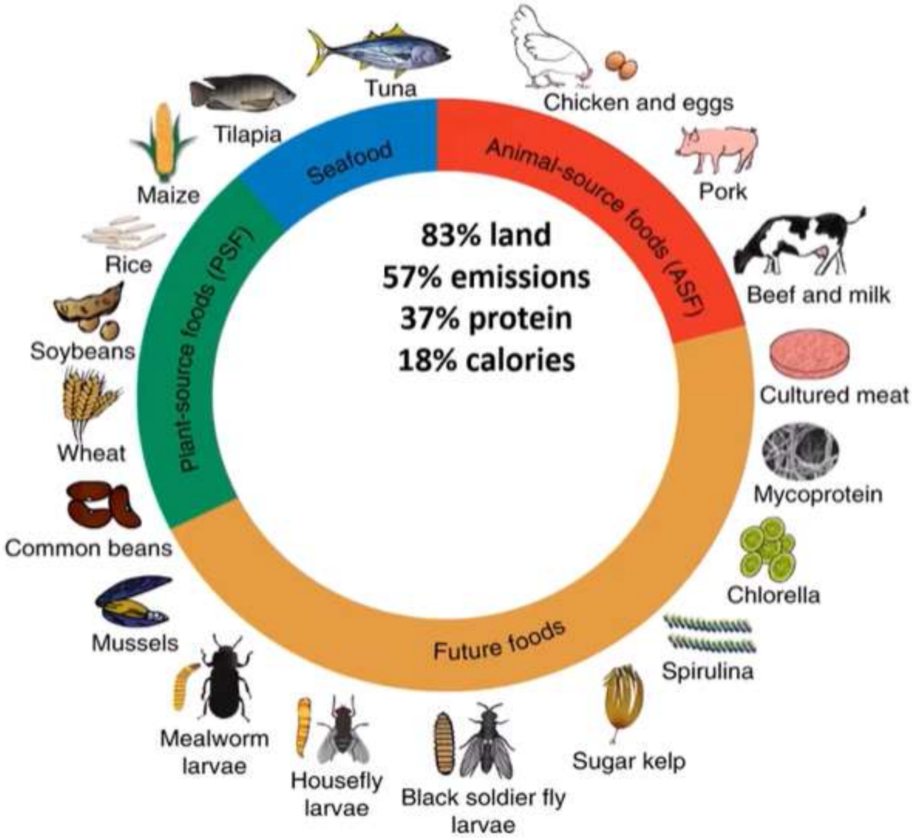

Fig.2. The projected structure of the world population's diet depending on the nature of the protein in 2030 [10]

In the next decade, the market for plant-based alternatives will take 10% of the global meat market. A Research and Markets report states that the vegan meat market will exceed $6 billion by 2023 [11].

The absence of allergens in the composition of food, «clean labels», «environmentally friendly products» are far from all that worries the modern consumer. Being choosy means not only choosing foods with a healthier list of ingredients, but also paying attention to packaging, production methods, how products are consumed, processed and delivered. Food choices have a big impact on your carbon footprint. It is most strongly increased by red meat, products transported over long distances (especially by plane). For these reasons, flexetarianism is becoming more and more common – an unwillingness to completely give up meat or dairy products, but an acknowledgment of the benefits of a plant-based diet. While vegans make up only a small part of the world's population, the concept of a flexitarian lifestyle is rapidly gaining popularity as a means of leading a healthier, more ethically conscious lifestyle without completely giving up your favorite meat. The main motivators for switching to plant foods are: concern for animal rights, concern for the environment, health benefits. In fact, 39% of consumers worldwide associate the term «natural» with herbal ingredients. Flexetarianism is divided into two currents – some prefer maximum naturalness, others want to use products that are organoleptically similar to meat. Vegetable cutlet or artificial meat? The world is no longer divided into meat eaters and vegans. By creating plant-based products that look and taste like meat, manufacturers support the culture of consuming traditional products that are familiar to us. So meat and vegan burgers can be served on the same menu and eaten at the same table [11].

The food industry faces the task of adapting alternative sources of protein, including artificial meat, to the needs of the population, developing new technologies and recipes for products using them. Of course, in order to actively distribute artificial meat on the food market, its cost must drop significantly, at least to the level of natural meat. The most important indicators are the safety and taste of the created product. Although various types of meat (chicken, turkey, pork, beef, foie gras, fish, seafood) are cultivated today, the taste is not always what you want. For the mass interest of consumers in new raw materials, scientifically based advertising is necessary, which will convince humanity of the great need to reduce the use of animal resources to meet food needs [12]. The estimated global cultured meat market will be USD 214 million by 2025 and USD 593 million by 2032 as the number of entrepreneurs establishing various startups is currently increasing daily. There are about 44 startups producing alternative protein in the world. At the same time, such large companies as Novozymes, DuPont and DSM are also developing a similar line of such products. Investors are betting that artificial meat and dairy products will rapidly increase production to meet the needs of a new climate-conscious generation that wants to reduce the impact of livestock farming on the planet. Of course, not all startups are supported by success, but many researchers do not stop despite failure, because they consider developments in this direction to be the most promising [8]. In Ukraine, a few years ago, the market of meat substitutes appeared, companies that manufacture products, in particular, for vegetarian establishments and stores. However, Ukraine has neither manufacturers nor technologies of competitive artificial meat. One of the global representatives of plant-based meat analogues present on the Ukrainian market is the company Beyond Meat, which released a burger based on pea protein, rice protein, and mung bean protein that imitates a beef patty. There are also other foreign (Garden Gourmet from Nestle, The Moving Mountains) and local producers (startups Eat Me At, Dynameat, Plantanix and such well-known producers as AVK with TM Dreameat, or Premier Food with a vegetable line from Mr. Grill, etc).

There are three types of artificial meat, which differ in nature and manufacturing technology (Table 2) [13].

Table 2

Artificial meat categories [13]

A type of a artificial meat	Definition
Plant-based meat substitutes	Vegetable and mycoproteins that are used as an alternative to meat, for example quorn, tofu
Cultured meat	Produced using in vitro culture tissues or cells (stem cells, myocytes)
Modified meat	Meat obtained from genetically modified organisms

First, there are meat substitutes made from alternative protein sources, known as «meat alternatives». Commonly used alternative sources of protein are plants and fungi (mycoproteins). The second is cultured meat, or in vitro meat, obtained from tissue and cells grown in laboratory conditions, and not in a living organism [13].

Genetically modified organisms can be considered as a third category of artificial meat. Despite the similarities with traditional meat production, animals whose genome has been artificially altered in the laboratory can be considered artificial or man-made and worthy of the discussion of artificial meat. Cloned animals belong to the fourth category of artificial meat. The meat of cloned animals can be considered natural, since it is simply a «scientific» form of obtaining identical offspring. However, the cloning process is «man-made», and the clone is a copy of the «parent» animal, and therefore the meat can be considered artificial.

In vitro meat recently received a lot of publicity in August 2013 after the production and tasting of the world's first «burger» made from stem cells grown in a tissue culture medium [9]. The discovery of stem cells made it possible to produce cells in vitro, which laid the theoretical foundation for cultured meat. Theoretically, under appropriate culture conditions such as growth factors, oxygen, nutrients and temperature, stem cells can proliferate to form multinucleated myotubes, then muscle fibers through further proliferation and differentiation. The muscle fiber finally matures into muscles, which can be processed into various products, such as sausage, beef steak, burger patty (Fig. 3).

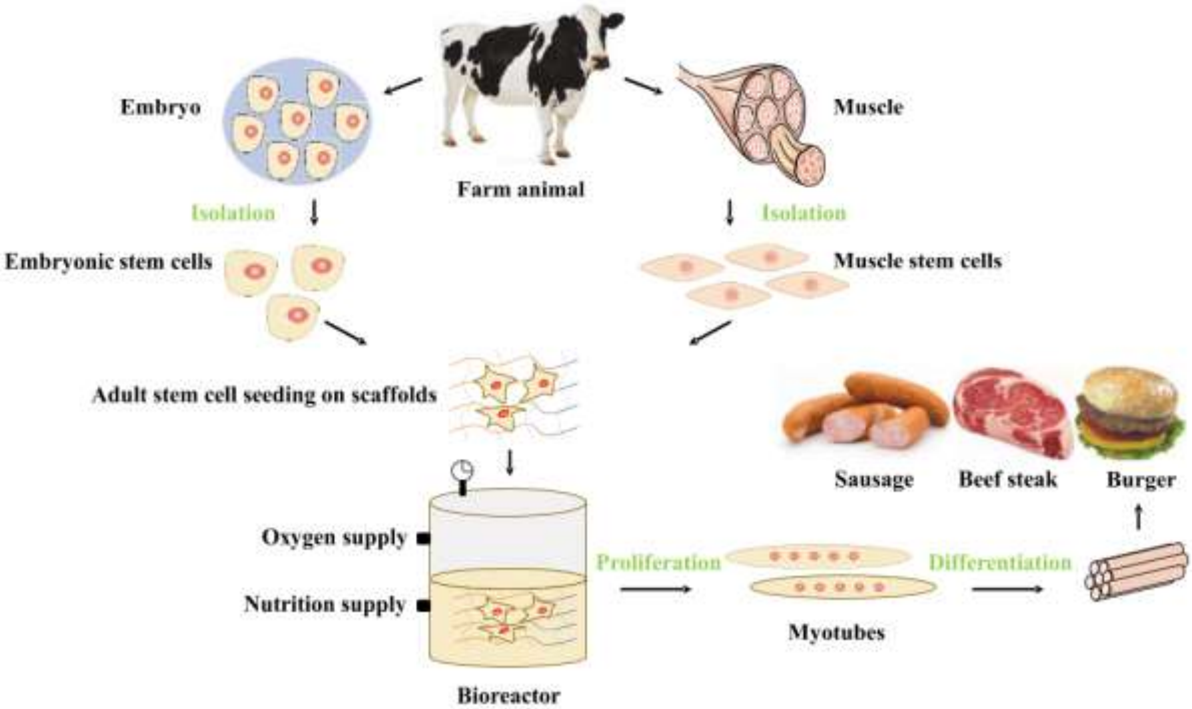

Fig.3. The process of growing meat

Various techniques exist for cultured meat production systems, including scaffolding, self-assembly, organ printing, and nanotechnology. The scaffold can be used as a carrier for satellite cells or myoblasts of animal embryos. This technology produces soft or boneless meat that can be used to make hamburgers and sausages [6]. The self-organizing technique can produce a very realistic three-dimensional meat structure, just like in the natural form of meat. An organ printing involves spraying living cells onto a gel, which is treated like printing paper. These cells can then fuse together to form three-dimensional structures of any shape. Nanotechnologists are developing nanorobots capable of selectively combining similar atoms or molecules into a whole structure. In theory, they can produce any substance of the desired form in their state. As one of the types of artificial meat, there is also plant-based meat. Plant-based meats are usually produced by extrusion, shear cell technology, wet pressing and electrospinning. Extrusion is the most commonly used method of converting plant materials into structural aggregates or fibers and then manufacturing them into meat substitutes due to its versatility, low cost, energy efficiency, and high productivity. Currently, new methods of microextrusion have been developed, which will allow to imitate the fibrous texture of real meat. According to a report by the Good Food Institute (GFI, USA), the extrusion method can be used to produce alternative plant-based products such as whole-meat meat (e.g., chicken breast, pork chop, steak) and products such as restructured meat. Meat (for example, nuggets, meatballs, meatballs) using textured vegetable proteins. After processing, three different structures can be observed: fibers, capillary-filled gel, or fiber-filled gel [7].

Although extrusion processing has been widely studied over the years, extrusion process control and extrusion product design are still largely based on empirical knowledge. The shear cell technique is a new technique based on the concept of flow-induced structuring. However, one of the problems with artificial meat is the sensory characteristics and nutritional value compared to conventional meat. Cultured meat is colorless, although the color can be improved by adding red beet juice and saffron [8]. It is also difficult to reproduce the taste of meat, which arises as a result of the complex interaction of proteins, carbohydrates and the lipid fraction. Like color and flavor, muscle texture is also difficult to imitate because texture is the result of many characteristics of meat, including tissue composition, microscopic and macroscopic tissue texture, and ability to retain water and fat during cooking. To achieve cultured meat that has a similar muscle texture, muscle fibers can be produced using tissue engineering and regenerative medicine techniques. Scaffolds with cross-striped textures imitating the inherent structure of muscles have been shown to promote the formation of myotubes. Although some scaffolds can be degraded or recycled by cells, which can thus affect the texture of cultured meat [9].

In addition, a significant problem in the production of competitive cultured meat is ensuring the presence of all the necessary components. Nutrients in cultured meat that are not synthesized by muscle cells must be supplemented. Minerals and vitamins that are not synthesized by muscle cells usually require a binding protein and efficient transport mechanisms to enter cells. Vitamin B12 and heme iron are particularly important substances from meat sources. The addition of the crystalline vitamin B12 produced by commercial microbial biosynthetic fermentation would be necessary for cultured meat grown in an aseptic environment. To provide iron in a bioavailable form to cultured muscle cells, it is important to supplement the medium with iron (III) bound to the plasma-binding protein, transferrin [12]. The biggest challenge is to create plant-based meat with a tender texture, improved water-holding capacity and meaty taste. The tenderness and texture of plant-based meat can be improved by adding fat and its substitutes. Emulsion gels, which are fat substitutes, have potential applications in plant-based meat products. The lack of taste of animal meat, both usual and expected by consumers, is another serious obstacle to the development of plant-based meat. Given that specific meat flavors contain more than 1000 water-soluble and fat-soluble components, imitating the true taste of meat is a significant challenge [13].

The cultured meat growing technology is due to the reproduction of the complex structure of cattle muscles with several cells. A biopsy is taken from a live animal. This piece of muscle is cut to release stem cells, which have the ability to proliferate but can also transform into different cell types, such as muscle and fat cells. The process of producing cultured meat in this way can be divided into four steps: obtaining cells, large-scale propagation of these cells, induced differentiation into mature cells in muscle tissues, and harvesting and food processing of all cultured cells into meat products. Cells will begin to divide after being cultured in an appropriate medium that is supplied with nutrients, hormones, and growth factors. It is known that the best medium contains bovine serum (FBS) [14].

With regard to philosophical and religious issues, the production of artificial meat still leaves behind debates about the possibility of considering it kosher (according to Jewish laws), halal (for Muslim consumers, which must meet the requirements of Islamic laws). Some believe that cultured meat can only be considered kosher if cells from a slaughtered kosher animal were used, while others suggest that regardless of the source of the cells, they lose their original identity during the culture process. The halal status of cultured meat can be determined by identifying the source of cells and serum. Accordingly, artificial meat will be considered halal only if the stem cells are taken from a halal slaughtered animal, and no blood was used in the cultivation process [15]. More than one trillion cells can be grown, and these cells naturally fuse to form myotubes, which are less than 0,3 mm in length. Next, the connected cells are placed in a ring that grows into a small piece of muscle tissue. This piece of muscle can multiply to more than a trillion filaments [14]. These fibers are attached to a spongy framework that infuses the fibers with nutrients and mechanically stretches them, “training” the muscle cells to increase their size and protein content. Based on this process, fewer animals will be needed to produce huge amounts of meat due to cell proliferation, which avoids killing too many animals, but enough calves if still using FBS serum. During this process, the cells are kept in a controlled environment that replicates the temperature inside the animal's body to accelerate the development of lab-grown meat [16; 17].

The production of artificial meat and the integrity of its technologies can only be considered successful if the animal raw materials are completely abandoned in its cultivation, because otherwise the new industry will still remain dependent on animal husbandry. The development of cell culture medium without the participation of FBS serum is currently proprietary information, although it is known that the main components are amino acids, mainly arginine and glutamine, glucose, insulin, inorganic salts, low-concentration vitamin compounds, growth hormones FGF-2 and TGF-β. Alternative ingredients such as yeast and microalgae extracts have shown progress in supplementing the cellular environment. This raw material makes it possible to reduce the amount of more expensive components, thereby significantly reducing production costs [9].

The appearance of this type of artificial meat is still far from real muscles, which are composed of organized fibers, blood vessels, nerves, connective tissue and fat cells. That's why different startups working in this field have developed different strategies: some work with stem or muscle cells to recreate disorganized muscle fibers, which is the simplest approach, while others try to recreate thin slices of muscle, that is, muscle fibers and other types of cells are quite well connected to each other. However, the production of a thick piece of meat like a real steak is still a dream, due to the need to introduce oxygen inside the meat to simulate oxygen diffusion as it occurs in real tissue [18, 19].

In addition, it is difficult to imagine that laboratory meat producers will be able to offer consumers a wide range of meats that reflect the variety of animal muscles or cuts in the near future. The sensory quality of meat differs between different species (pork, poultry, lamb, beef, rabbit, etc.), as well as within species, between breeds, sexes, types of animals (young bulls, bulls, heifers and cows as an example of cattle) , growing conditions and mainly between muscles with different anatomical locations. Consequently, many complex processes still need to be controlled to make in vitro meat more attractive to consumers, as is the case with any other new food product [20].

Today, scientists are actively researching two main methods of artificially growing muscle cells – the scaffolding technique and 3D/4D bioprinting.

Scaffolding technique – isolating embryonic myoblasts from farm animals such as cattle, sheep and pigs and allowing them to grow in a stationary or rotating bioreactor using a plant-based culture medium, which would be required for a scaffold-based in vitro meat production system. These cells will divide for weeks or months, eventually becoming muscle fibers on a scaffold in a bioreactor [21].

A large bioreactor capable of mass culturing meat has yet to be designed and built. Building muscle requires using the circulatory system to deliver nutrients and oxygen to developing and growing cells while removing metabolic waste. Although the tiny pieces of muscle receive enough nutrients and oxygen through diffusion, muscles with built-in blood arteries do not develop.

Although several methods of cell cultivation are already available, the most difficult step at in vitro meat production is determining the optimal composition of the culture medium. The medium should be inexpensive, consist entirely of nutritional components, be widely available in large quantities, and be effective in the maintenance and development, proliferation, and differentiation of muscle cells [22].

3D/4D bioprinting is three-dimensional (3D) or four-dimensional (4D) bioprinting based on conventional printing principles. Software for automated design (CAD) is used to create a prototype of a bioproduct. Cells are dispersed on a gel according to CAD, and during culture the cells fuse to form a bioproduct that can have a basic cellular structure and vascularization for blood delivery [23]. 3D bioprinting is one of the most effective and attractive methods for creating functionally and anatomically identical organs or tissues for regenerative therapeutic applications in tissues and organs. It precisely deposits biomaterials and different cell types into a single 3D tissue architecture. 4D printing, which uses comparable technology, extends 3D printing and adds another dimension of change over time. Target organs or tissues are sensitive to humidity and temperature, and this method is used to repair muscle, bone, and cardiovascular tissue [24].

In 2021, Aleph Farms, in collaboration with the Technion, Israel Institute of Technology, successfully cultivated the world's first ribeye steak using 3D bioprinting. It has fat similar to regular meat, is tender and juicy. The company also claims that in the future it will be able to produce any type of meat using this technology [25].

Analyzing the production process of artificial meat, it is possible to distinguish three main advantages over natural meat: the safety of its consumption, the exclusion of animal vaccination, the possibility of controlling the nutritional value of the grown product.

Safety for consumers. Proponents of in vitro meat claim that it is safer than conventional meat, based on the fact that lab-grown meat is produced in an environment completely controlled by the researchers or producers, without any other organisms, whereas ordinary meat is the part of the animal in contact with the outside world, although the muscles and tissues of every animal are protected by skin and mucous membranes. Indeed, cultured muscle cells have none of the potential contamination that occurs during animal slaughter, nor the possibility of encountering enteric pathogens such as E. coli, Salmonella or Campylobacter, which are the main cause of millions of episodes of illness each year. However, scientists or manufacturers can never control the entire production chain, and any mistake can have dramatic consequences in the event of a human health problem. Today, this is often found in the industrial production of minced meat [26].

There is no need for vaccinations. Another positive aspect related to the safety of cultured meat is that it is not produced from animals raised in a confined space, so the risk of disease outbreaks is eliminated and there is no need to carry out expensive vaccinations against diseases.

On the other hand, it is the cells, not the animals, that live in large numbers in cultured meat incubators. Unfortunately, scientists do not know all the public health implications of cultured meat, as in vitro meat is a new product. Some authors claim that the process of cell cultivation can never be perfectly controlled, as some unexpected biological mechanisms may arise. For example, given the large number of cell proliferations, it is likely that some dysregulation of cell lines occurs, as occurs in cancer cells, although it is conceivable that deregulated cell lines could be harvested for production or consumption. This may have unknown potential effects on muscle structure and possibly human metabolism and health when consuming meat in vitro [18]. However, it is possible to control the chemical composition and nutritional value of such meat. Thus, the nutritional value of cultured meat can be easily controlled by adjusting the fat components – the ratio between saturated fatty acids and polyunsaturated fatty acids [27]. In addition, no strategy has been developed to enrich cultured meat with certain trace elements characteristic of animal products (such as vitamin B12 and iron. In addition, the positive effect of any nutrient can be enhanced if it is introduced into an appropriate matrix. In the case of in vitro meat, there is uncertainty that other biological compounds and the way they are organized in cultured cells can enhance the beneficial effects of micronutrients on human health. Thus, a good understanding of the uptake of micronutrients (e.g., iron) by cultured cells is needed. It cannot be excluded that the health benefits of trace elements are reduced due to the nutrient medium, depending on its composition [28].

Plant-based meat substitutes are more widely available on the world market. Supporters of this segment of products are vegetarians, but the assortment of these products in supermarkets and ecological stores increases every year, as an increasing number of people, concerned about their health, strive to change their diet towards naturalness by replacing animal protein with vegetable, balanced products and reducing calorie content.

The most popular raw material for this segment of the market is soy meat (textured vegetable protein), which is soy protein with a fibrous consistency similar to regular meat and contains more than 50 % protein. Soy protein products have become popular due to their low price, high nutritional value and the possibility of various uses. There are two important compounds: soy protein concentrate (minimum protein content 65 % by dry weight) and soy protein isolate (minimum protein content 90 %) [29]. Soy meat is made by combining soy protein with water at 30°C in an extruder for 3 hours to remove anti-nutritional substances. The material is cleaned, heated and denatured to produce a loose solid which is later dried. To create a well-textured structure, the temperature in the processing section is usually maintained at 70°C for 5–8 hours. Thermoextrusion is the most widely used method due to its low cost, energy efficiency, adaptability and high productivity. This is the main processing method used to convert plant proteins into structured fibrils for further meat substitute products. Thermoextrusion can be extrusion with low, medium and high humidity [30].

Thermoextrusion is a multipurpose procedure that includes expansion, molding, heating, deaeration, homogenization, compression, shear, hydration, and mixing. At elevated temperatures (140–180 °C) and from moderate to high moisture concentration (40–80 %), extrusion is carried out by a complex shear process due to protein texturing and subsequent formation of fiber structures. These circumstances allow precise control of product expansion and protein gelation, fiber shape, fat emulsification, and particle restructuring. The extrusion process leads to microcoagulation and fibrillation of protein components [31].

Meat alternative – Quorn is made from mycoprotein, the main component of which is Fusarium venenatum, a fungus found in the soil. The mushroom is fermented with sugar and centrifuged to produce a paste that is used in various products. Quorn food includes vegan alternatives to pies, nuggets, patties, steaks, burgers and ready meals such as lasagne. Compared to other vegetarian sources of protein, they have no cholesterol, are low in saturated fat, have a healthy fatty acid profile, and are high in fiber. In addition, the content of amino acids and mycoprotein is similar to other vegetarian and animal proteins [32].

Tofu is a well-known meat substitute made from soybeans that is rich in nutrients such as protein, calcium, and iron. Tofu is obtained by coagulation of soy milk with $CaSO_4$ or $MgCl_2$ and contains about 8 % protein, 4–5 % lipids, 2 % carbohydrates and about 1 % dietary fiber content. When fresh, vital vitamins and minerals can be added to tofu to provide a variety of nutritional and physiological benefits. In the United States, there are rice burgers and sausages called risofu, which were developed in the Shan region of Thailand, where rice-based tofu is produced. Risofu combines brown, wild and white rice to maximize nutrients [33; 34].

Tempeh is the most well-know fermented food with a high content of nutrients and biologically active compounds. Tempeh is made by soaking and cooking soybeans, to which mushrooms are later added. After 24 hours, the tempeh will have a nutty taste and a chewy mushroom consistency, which is then used to make cutlets and other meat substitutes. The protein content of tempeh is greatly increased during fermentation, for more complete absorption compared to unfermented soybeans. Tempeh is the product of a mixed fermentation process involving yeasts, molds, various microorganisms, gram-negative bacteria and lactic acid, although the dominant component is Rhizopus oligosporus. [35].

Kinema is a fermented food that is alkaline and sticky due to the use of the Bacillus fungus during fermentation. In terms of dry weight, kinema has 62 % moisture and contains about 7 % ash, 17 % fat, 28 % carbohydrates and 48 % protein [36].

Wheat gluten (wheat meat or *seitan*) is a popular meat substitute consisting of gluten extracted from wheat. Seitan has the most meat-like consistency and is used in vegan substitutes for hamburgers, sausages, schnitzels, minced meat, nuggets and other meat-like products. In addition, in most countries, wheat is the main grain raw material, so the production of seitan is available all over the world. Seitan is prepared by adjusting the water content of the wheat flour mixture from 40 to 80 % to activate the gluten, and then removing the starch from the mixture, leaving only the gluten [37].

An alternative and promising source of complete protein are *insects*, the products of which are currently being actively distributed. Insects and arachnids that are eaten around the world include crickets, cicadas, grasshoppers, ants, various beetles, larvae of various types of caterpillars, scorpions, and tarantulas [38]. Insects that are used for food are grown on special farms in compliance with sanitary conditions. It is known that the cultivation of insects in comparison with cattle has a positive effect on the atmosphere. Such farms produce 300 times less nitrous oxide, 10 times less methane and much less ammonia. Whole insects, powder, flour and oil from insects are used as food. The market offers a selection of flour and confectionery products, snacks and chips, protein bars, drinks and cocktails made from insects [39].

In Ukraine, the market of alternative products is only in its infancy, but the first steps in this direction have already been taken. On the shelves of supermarkets you can already find not only plant-based milk and tofu, but also plant-based meat patties, coconut cheese and even tuna. Finally, another incredible innovation is vegetable protein from red seaweed (Zotter company, USA). Algae are perfect for creating meat alternatives due to their color, high protein content and taste. «Algae can produce five times more protein than soy. Seaweed can literally feed the world!» says oceanographer and entrepreneur Beth Zotter. In addition, some algae contain vitamin B12, so the production plans to find a way to preserve it and make it absorbable [40].

An analysis of the plant raw material market indicates an increase in the popularity of products with *algae* to replace animal protein. Today, macro- and microalgae of various species and strains are used as food. They serve as full-fledged components of dishes and drinks, and are also used as a biologically active supplement to the diet or in the form of a dye. Green microalgae chlorella and spirulina, which are rich in high-quality protein (50–70%), as well as a wide range of amino acids, vitamins, minerals and pigments, are currently enjoying world popularity, which gives them full prospects in the improvement of various food products. What is important is that this raw material is really recognized among vegetarians and supporters of healthy food. Among the assortment of products with microalgae are snacks, sauces, dry soups, bakery and confectionery products, pasta, lemonades, smoothies, isotonic drinks, candies, gums, and others [41; 42]. The technology for the production of meat analogues is aimed at creating plant-based alternatives or whole-muscle raw materials as close as possible in taste and consistency to real meat [43].

Genetically modified organisms can be considered a *third class of artificial meat.* Despite their similarities, animals whose genome has been intentionally altered in a laboratory should be considered artificial. Cloned animals are the *fourth class of artificial meat*. Cloning is only a scientific and auxiliary approach to obtaining identical offspring. Since this is a man-made procedure and the meat can be considered artificial.

Cloning animals allows the propagation of existing genetics by increasing the number of animals with a certain genotype and reducing carbon emissions. Cloning animals with good genetics can complement other strategies, such as genetic manipulation, but may have some negative consequences related to animal conservation. However, the cloning process is not without its drawbacks, with some deformities such as large offspring syndrome (LOS) and premature deaths being a direct result of cloning technology [44]. A colossal problem for the industrial introduction of GMOs is their licensing. Although the domestication of genetically modified animals has been the subject of recent research, the idea has not been embraced or approved. Such obstacles negatively affect the return on investment, although the cultivation of genetically modified livestock does not require significant investment in infrastructure, the main costs are related to the distribution of the product among the population [45]. Products made by artificially growing meat are presented in Table 3.

Table 3

Assortment of artificial meat, produced using the technology of artificial cultivation

Producer	Country	Direction
Clear meat	India	Poultry
Eat just	Great Britain	Meat
Future meat Technologies	Israel	Meat
Higher steaks	Great Britain	Pork
Mirai foods	Switzerland	Beef
Mosa meat	Netherlands	Beef
Shiok meats	Singapore	Shrimps
Supermeat	Israel	Poultry
Aleph farms	Israel	Beef
Biotech foods	Spain	Pork
IntegriCulture, Inc.	Japan	Duck or goose liver
Vow	Australia	Kangaroo

Cultured artificial meat consumption is already widespread in Europe. The leader in consumption of this product is the Netherlands. Today, the Netherlands has a rich ecosystem of cultivated startups, food manufacturers, research centers, universities and non-profit organizations that support cellular agriculture. Recently, the artificial meat of the Singaporean manufacturer Eat Just went on sale in the Ukrainian and world markets. This is artificial chicken, which Singaporean restaurants will use primarily for the production of nuggets [46].

One of the manufacturers of artificial meat printed on a 3D printer is the Israeli startup Redefine Meat. Bioengineer Giuseppe Sionti, one of the creators of the startup Novameat Tech SL, prints steaks from rice, peas and seaweed on a 3D printer. The startup Zhenmeat was founded in 2018. It is China's first and leading plant-based meat startup, creating sustainable protein substitutes tailored to China's needs. Its products include plant-based pork, sausages and meatballs made from pea protein, mushrooms, cellulose, coconut oil, and various natural flavors and spices. Zhenmeat is also working on vegan crawfish and pork tenderloin. Their products are now sold online and through various partner restaurants in China. Beyond Meat, a producer of artificial plant-based meat, presented its products on the Ukrainian market. This startup focused on creating burger patties based on the plant-based ingredients shown in Figure 4.

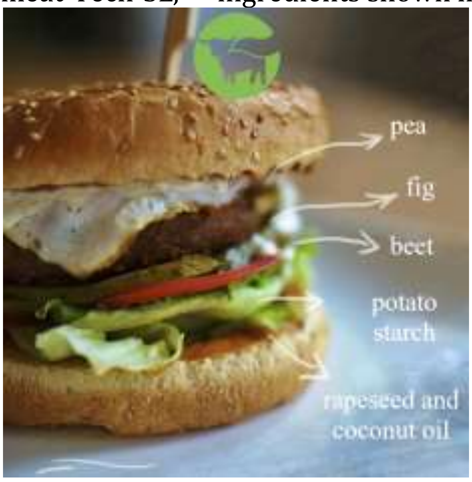

Fig.4. The main components of the artificial vegetable meat of the manufacturer Beyond Meat

Another interesting product innovation is Tammik Fermented Oat Protein. Fermentation increases the nutritional value and digestibility and improves the texture of the product. This will make the vegetable meat attractive. One of the pain points for anyone transitioning to a plant-based diet is seafood, as the flavor is really hard to come by in a plant-based diet. Indeed, the combination of tofu and nori imitates the taste of sea dishes in an interesting way. But even here there is an opportunity to try real fish without harming the animals. First, there are already vegetable analogues of tuna, shrimp and crab meat. And recently, three Austrian students founded the startup LegendaryVish and are printing plant-based salmon on a 3D printer. Another company – Kuleana – has developed a technology for the production of vegetable tuna from algae, which tastes like natural fish, so it will be suitable for making sushi. The growing of laboratory meat and fish is also progressively developing. For example, California-based startup BlueNalu is creating seafood alternatives using live fish cells. The animal is anesthetized and a cell sample is taken from which billions of similar cells can be grown. The only difference between an artificial fish fillet and a regular one is that the product does not have bones. Also free of mercury, parasites, microplastics and bacteria. Creating such an artificial fillet can help solve the problem of high fish catch. And very soon it will be possible to try chicken nuggets grown in this way from KFC. The company is developing and plans to test this fall and promises that the product will be as close as possible to the usual in texture and taste [48].

British startup Higher Steaks has created the world's first lab-grown bacon [49]. The startup uses unique technology to create realistic and nutritious vegan cheese from local ingredients like cauliflower and hemp. The company uses all parts of the cauliflower, various fermentation methods and a variety of natural ingredients to achieve a cheesy taste. Grounded has already developed 35 varieties of cheese, but will launch three first: hemp cream cheese and feta, as well as a vegan cheese sauce [50].

There are many ways you can replace an egg in baking, such as adding soaked flax or banana to baking, making an omelette with tofu or chickpea flour, or making marshmallows or cream with aquafaba (chickpeas or chickpeas). This was not enough for the French biologists of the Philippines Suler and Cherilene Tavizuk, and they developed an egg from legumes, founded a company for the production of such eggs called Les Merveilloeufs. The Les Merveilloeufs egg has a realistic shell and can serve as a substitute for a normal one - it can be fried, boiled and added to the dough. This is far from the only company that specializes in the development of egg substitutes. For example, Indian manufacturer EVO Foods makes eggs from lentils [51].

The most common Ukrainian meat substitute is tofu, the main producers of tofu in Ukraine are: VforVegan, Зелена Корова, Vegetus, Vegi Land, Ideal Nemoloko.

In particular, the manufacturer «Зелена Корова» offers the consumer the following types of tofu: classic, with vegetables, with curry, fried and smoked, and also produces products made of artificial vegetable meat for vegans. Figure 5 shows the plant-based products of the company: artificial meat sausage (based on tofu and soy isolate), burger patties (based on pea protein) and fish sticks (based on rice texture) [52].

Fig.5. Alternative meat products on a plant basis from the manufacturer «Зелена Корова»

The production of plant-based artificial meat is very common in Ukraine, in contrast to cultured and genetically modified meat. Regarding Europe, it is worth noting that cultured meat has received the appropriate approval from the European Food Safety Authority (EFSA). Recently, interest in the development and clear rules for the production and sale of cellular meat in the EU is one of the priorities and encourages a number of associations and companies to work. The concept of cellular meat strongly calls for the fastest possible approval and permission to commercially implement this type of product [53]. In the USA, the regulatory management of the quality of cultured meat is carried out by two agencies. Since 2018, the Food and Drug Administration (FDA) and the United States Department of Agriculture (USDA) have issued a joint regulation on artificial meat. Oversight of cell culture, growth medium, harvesting, isolation of cells, i.e. the stage before obtaining a product from bioreactors, is established by the FDA. USDA is responsible for the following stages of production, including labeling. It is important that in terms of general requirements for the final artificial product, the same quality and safety rules apply as for any traditional meat product [54]. In Canada, placing cultured meat on the market requires the producer to provide specific information. After receiving the artificial product, tests are carried out to confirm that the product is safe for consumption, as well as information about allergens, levels of chemical contaminants, etc. Only after providing the product verification documentation, it can receive permission for its use and introduction to the market [55].

Asian countries reacted extremely quickly to the dynamic development of the artificial meat market by introducing complex legal regulations that allow the production and sale of finished products. The Singapore Food Agency (SFA) has introduced guidance on novel food requirements requiring detailed information to be provided for the approval of cultured meat. Manufacturers are required to conduct a protein safety assessment due to potential food safety risks related to allergenicity, toxicity, safety of production methods, and dietary exposure resulting from consumption. They must also provide detailed information on the materials and reagents used in the manufacturing processes. The SFA now assesses applications on an individual basis. Labeling requirements are also important. Companies selling alternative protein products in Singapore must label them with clarifying names such as «cultured» or «plant-based» to indicate their origin and enable consumers to make an informed choice about whether to consume such products [56]. The Japanese government is working on developing a special regulatory framework to properly shape the cultured meat market while ensuring food safety and consumer consent. Japan's Ministry of Health has begun regulating the approval process. A team of experts is trying to decide what regulations might be necessary and really effective in researching the safety of the cultivation process, and whether the artificial product could have a negative impact on human health. This is one of the first steps towards the commercialization and industrialization of acellular meat in Japan [56].

Conclusions

Artificial meat technologies are advancing at a breakneck pace to raise customer expectations for health, environmental sustainability and animal welfare. The production of cultured meat products of suitable quality will soon be possible, although large-scale production still seems difficult and likely to take time even if possible. Artificial intelligence-assisted cultured meat production is one potential answer. It is impossible to close the imbalance between supply and demand with traditional meat production in the face of rapid population growth and a significant protein deficit. Artificial meat production should be aimed at supplying ecologically clean, completely safe, disease-free and chemically balanced meat.

Currently, the only products available to consumers are plant-based meat substitutes. In the near future, the traditional production of meat with the participation of animals is unlikely to be stopped, but the demand between consumers and the range of protein vegetable substitutes is developing rapidly.

Artificial meat production has already faced many hurdles, but it still has a long way to go before it becomes a commercial reality, with societal acceptance, expanded production methods, and lower costs. Many technologies are not yet suitable for mass use and do not have regulatory laws. Although cultured meat attracts animal rights activists, several animals must still be killed to harvest the stem cells, which is why researchers are actively testing alternative raw materials to completely eliminate animal husbandry in production. In order to transform artificial meat into a large-scale industry and replace conventional production, detailed, thorough and extensive research, support and investment from government and industry is required. Different consumer groups are demanding different modifications to current meat production practices, and it would be detrimental to the industry to ignore any of these pressures. Regulators are also introducing new, environmental legislation that is changing the economics of production. Artificial meat technologies use innovative methods and technologies to meet changing consumer demands, which include environmental sustainability, health concerns and animal welfare.

However, there are many barriers before these products can reach the market on a large scale. Many products rely on unproven technology, are not ready for commercial use, or struggle with government regulations and thus have yet to find a place in the industry. The market place is large and diverse, with many different consumer groups demanding different products. The products that are best suited to these markets will outcompete other products and determine the future of the meat industry. Currently, the only products that are widely available to consumers are meat substitutes made from plant proteins and mycoproteins. Although conventional animal meat production is unlikely ever to be completely eliminated, not least due to the unique ability of ruminants to digest cellulose, the industry will face a challenging market and regulatory environment that is leading to changes in the industry as a whole.

Traditional more extensive livestock systems (pasture-based beef and lamb) will need to develop improved systems for transparent cash transaction and feedback to ensure increased efficiency and quality of «market pull».

There is growing recognition that the current approach is unsustainable. Innovations in two specific areas, cultured meat and plant-based meat, promise a revolution in the food system. These areas represent huge market opportunities for profit and significant prospects in solving urgent problems related to the global food supply. These areas are sustainable, humane and safe, with benefits including animal welfare, process monitoring, environmental sustainability, food production efficiency, reduction of intensive land use and greenhouse gas emissions.

However, several aspects of this direction should be explored:

1. Relevant information should be communicated to a wide range of consumers through media reports, product introductions, and the dissemination of scientific awareness through debates and discussions about the new technology;

2. It is necessary to pay attention to the technology of scaling up production and processing, as well as to the process of storage, packaging, regarding the stability and quality of the finished product, checking the quality and purpose before these products are commercially implemented;

3. Develop real-time techniques to monitor the amount of nutrients and waste in the culture medium to determine exactly when and how much medium can be recycled to reduce costs.

To compete effectively with traditional meat products, the plant-based meat industry must expand, innovate, and develop substitutes that are as tasty and affordable as conventional meat products. There are more opportunities for innovation in the plant-based meat industry than in the traditional one.

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