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Biotechnology in Sports

Matthew N. O. Sadiku[1], Paul A. Adekunte[2], Janet O. Sadiku[3]

[1]Roy G. Perry College of Engineering, Prairie View A&M University, Prairie View, TX, USA
[2]International Institute of Professional Security, Lagos, Nigeria
[3]Juliana King University, Houston, TX, USA

ABSTRACT

Biotechnology involves the application of biological sciences, genetic engineering, molecular biology, biochemistry, and other advanced technologies to develop products and processes that improve human health and performance. It is an emerging field that is transforming the world of sports by improving athletic performance, preventing injuries, accelerating recovery, and promoting athletes' health and well-being. In sports, biotechnology provides innovative approaches to understanding the human body, optimizing physical capabilities, and addressing health challenges associated with athletic activities. As sports become increasingly competitive and technologically advanced, biotechnology is playing an important role in sports medicine, nutrition, rehabilitation, and personalized training. Biotechnology has considerable potential to transform sports through improved healthcare, injury prevention, rehabilitation, personalized nutrition, and scientific understanding of athletic performance. This paper aims to provide a comprehensive framework for implementing sports biotechnology.

KEYWORDS: *sports, sports industry, entertainment, biotechnology, sports biotechnology, digital health.*

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INTRODUCTION

Biotechnology is the application of biological processes, organisms, or systems to produce products or services that benefit human health, agriculture, or the environment. It encompasses various disciplines such as medical, agricultural, industrial, environmental, pharmaceutical, animal, genetic engineering, and bioinformatics. Sports biotechnology is a branch of biotechnology that focuses on enhancing the performance, health, and well-being of athletes and sports enthusiasts. It refers to the application of biological knowledge, techniques, and innovations to improve athletic health, performance, training, and recovery. It combines disciplines such as genetics, molecular biology, physiology, bioinformatics, and biomedical engineering to understand how the human body responds to exercise and physical stress. The multidisciplinary nature of biotechnology is illustrated in Figure 1 [1].

Biotechnology is significantly transforming the sports industry by enhancing athlete performance and recovery. It is reshaping how athletes train, recover, and compete, leading to improved health outcomes and performance metrics. This field encompasses various techniques and innovations aimed at improving health, preventing injuries, and optimizing training outcomes for athletes. The demand for new drugs is a major incentive for the explosive growth in the biotechnology industry. Biotechnology also supports the development of advanced medical treatments, nutritional products, biological monitoring systems, and diagnostic tools. These innovations help athletes maintain physical fitness, recover from injuries, and reduce the risk of long-term health problems [2].

WHAT IS BIOTECHNOLOGY?

Biotechnology is technology that utilizes biological systems or living organisms to develop products. It is basically applied biology that forms the interface between biology and engineering. It is the one of the most rapidly growing field of technology today.

Biotechnology pervades almost all aspects of our daily life; it affects the foods we eat, the safety of the water we drink, the clothes we wear, the medications we take, etc.

Biotechnology can roughly be divided into three main parts [3]:

- *Green Biotechnology*: This involves agricultural processes. The foundation of green biotech is crop improvement and production of novel products in plants.

- *Red Biotechnology*: This involves healthcare processes. It uses the human body's own tools and weapons to fight diseases.

- *White Biotechnology*: This field is connected with industry and environmental processes. Most of the white biotech processes results in the saving of water, energy, chemicals and in the reduction of waste.

Popular biotech fields include [4,5]:

-*Genetic engineering:* This is the direct manipulation of DNA molecules to produce modified plants, animals, or other organisms using biotechnology. Through genetic engineering, organisms can be given targeted combinations of new genes.

-*Tissue culture*: This is a method where by fragments of tissue from an animal or plant are transferred to an artificial environment to continue to survive and function.

-*Cloning:* This describes the process (of breeding) used to create an exact genetic replica of another cell. There are three different types of cloning: (a) Gene cloning, which creates copies of genes, (b) Reproductive cloning, which creates copies of whole animals, (c) Therapeutic cloning which creates embryonic stem cells.

Humankind has used biotechnology in several areas such as agriculture, healthcare, environment, and industrial biotech. The relationships between these various applications are shown in the biotechnology tree in Figure 2 [6]. Figure 3 is a representation of biotechnology [7], while Figure 4 shows the classification of biotechnology sector [8].

BIOTECHNOLOGY IN SPORTS

Biotechnology is one of the emerging technologies transforming the world of sports. As modern sports become increasingly competitive, athletes, coaches, sports scientists, and healthcare professionals are exploring biotechnology to improve physical fitness, endurance, strength, and recovery. Biotechnology has become an important contributor to the development of modern sports. It combines knowledge from biology, medicine, genetics, and technology to help athletes achieve their potential while maintaining good health. It provides scientific tools for understanding how the human body responds to exercise, adapts to physical demands, and recovers from injuries. It also creates opportunities for developing innovative medical treatments and improving the long-term health of athletes. Although many applications are already established, others remain experimental and require additional research to confirm their safety and effectiveness. As biotechnology continues to advance, its responsible application will help create a sports environment that is safer, healthier, more scientifically informed, and more supportive of human athletic potential [2].

Sports biotechnology can help athletes achieve their optimal potential by improving their physical, mental, and physiological attributes. For example, gene therapy can be used to modify the expression of certain genes that affect muscle strength, endurance, or recovery. Sports biotechnology is a rapidly evolving field that offers many opportunities and challenges for the future of sports. It has the potential to revolutionize the way we play, watch, and enjoy sports. It can help athletes prevent or recover from injuries and diseases by enhancing their immune system, healing process, or pain management. It can help sports enthusiasts enjoy their hobbies or activities by providing them with better equipment, clothing, or accessories [9]. Figure 5 shows some athletes [10].

APPLICATIONS OF BIOTECHNOLOGY IN SPORTS

Biotechnology has numerous applications in sports, ranging from personalized training to advanced injury treatment. It has become an important contributor to the development of modern sports through its applications in genetic research, injury prevention, rehabilitation, sports nutrition, doping detection, physiological monitoring, and personalized medicine. Common applications of biotechnology in sports therefore include the following [2,9,10]:

- *Genetic Testing*: Genetic testing is one of the emerging applications of biotechnology in sports. Scientists study genetic variations that may influence muscle composition, oxygen utilization, metabolism, and responses to exercise. For example, variations in genes such as ACTN3 and ACE have been studied in relation to muscle function and endurance-related characteristics. Genetic information may contribute to research on individual differences in athletic performance.
- *Injury Prevention:* Biotechnology plays an important role in preventing and treating sports injuries. Biological research helps medical professionals understand the mechanisms of muscle damage, ligament injuries, inflammation, and tissue repair. Regenerative medicine is an important area of sports biotechnology. Techniques such as platelet-rich plasma (PRP)

therapy and experimental stem-cell-based treatments are being investigated for their potential to support tissue healing. Figure 6 shows an injured athlete [11].

- *Sports Recovery*: The field of biotechnology is transforming sports recovery. From bioengineering to molecular techniques, these advancements facilitate healing and speed up recovery processes. In the fast-paced world of athletics, where every second counts and every movement matters, recovery can make the difference between winning and losing. Recovery is crucial for athletes. It allows muscles to repair, adapt, and ultimately improve after rigorous training sessions or competitions. Proper recovery minimizes the risks of injuries, exhaustion, and burnout. Figure 7 shows laboratory equipment assisting in sports recovery research [10].
- *Sports Nutrition*: Nutrition is essential for athletic performance, and biotechnology contributes to the development of specialized nutritional products. Through fermentation, enzyme technology, and other biological processes, scientists can produce proteins, amino acids, vitamins, and other nutritional ingredients. For example, biotechnology can support the production of alternative protein sources and specialized nutritional formulations designed to meet athletes' dietary needs.
- *Regenerative Medicine*: Regenerative medicine seeks to repair, replace, or regenerate damaged biological tissues. In sports, researchers are investigating the use of stem cells, growth factors, biomaterials, and tissue engineering to address injuries involving muscles, cartilage, tendons, and bones. For example, tissue engineering may eventually help restore damaged cartilage in athletes suffering from serious knee injuries. Although these technologies offer considerable promise, many remain experimental and require further clinical investigation before they can become established treatments.
- *Personalized Sports Medicine*: Biotechnology contributes to personalized sports medicine by providing biological information that may improve medical decisions. For example, molecular diagnostics can help identify certain inherited health conditions that may affect an athlete's safety during intense physical activity. Pharmacogenomics, which examines how genetic differences influence responses to medications, may also become increasingly useful in sports healthcare. Personalized medicine seeks to improve treatment effectiveness while minimizing unnecessary interventions and adverse effects. Figure 8 compares conventional sport medicine with personalized type [12].
- *Personalized Nutrition*: By analyzing the genetic profile, microbiome, and metabolic markers of each individual, biotechnology can provide customized dietary recommendations and supplements that suit their specific needs and goals. Personalized nutrition can also help prevent or treat common sports-related conditions, such as inflammation, oxidative stress, dehydration, or muscle damage. Biotechnology can also create new types of foods or modify existing ones to enhance their nutritional value, taste, texture, or shelf-life. Figure 9 shows sports nutrition products optimized for athlete performance [10].
- *Doping Detection*: Biotechnology is widely applied in detecting the illegal use of performance-enhancing substances in sports. Advanced laboratory techniques, including mass spectrometry, immunoassays, and molecular analysis, help anti-doping organizations identify prohibited drugs and biological manipulation. These methods can detect substances such as anabolic steroids, certain peptide hormones, and other prohibited compounds. Researchers are developing methods to detect gene doping, which involves the misuse of genetic technologies to enhance athletic performance. These applications help protect fair competition, discourage dangerous practices, and maintain public confidence in sporting events.
- *Cardiovascular Performance*: Athletes are at an elevated risk for cardiovascular conditions due to factors like intense training, immobilization following injuries, and extended travel. Biotechnology contributes to research on the biological mechanisms responsible for endurance and cardiovascular performance. Scientists study oxygen transport, mitochondrial activity, energy metabolism, and molecular responses to aerobic training. Blood tests and other physiological assessments can help identify factors such as iron deficiency that may affect endurance performance. Biotechnology can support the development of individualized training and recovery strategies, although attempts to artificially manipulate oxygen-carrying capacity or other biological systems may violate anti-doping regulations and create serious health risks.
- *Energy Harvesting*: Biotechnology can also harness the energy that is generated or wasted by the body during physical activity or rest. For example, biotechnology can develop devices or

materials that can capture or convert the heat, sweat, or motion of the body into electricity, light, or sound, which can power wearable sensors, gadgets, or implants, or provide feedback, stimulation, or entertainment. Energy harvesting can also create systems or networks that can transfer or share the energy among different individuals or devices, creating a more sustainable and interactive environment.

BENEFITS

Biotechnology offers several important benefits to athletes, coaches, healthcare professionals, and sporting organizations. Its benefits include enhanced athletic performance, improved injury prevention, faster and more effective rehabilitation, personalized training, better nutrition, early detection of health problems, and advances in sports medicine. Other benefits of biotechnology in sports therefore include the following [2,9,13]:

- *Enhanced Performance*: One of the major benefits of biotechnology in sports is its potential to improve athletic performance. Through physiological testing, biochemical analysis, and other biological assessments, sports scientists can better understand how athletes' bodies respond to exercise, training, and competition. This information helps coaches develop training programs that improve strength, endurance, speed, flexibility, and overall physical fitness.
- *Injury Prevention:* Biotechnology plays an important role in preventing sports-related injuries. Athletes frequently experience injuries involving muscles, bones, tendons, ligaments, and joints because of repetitive movements, excessive training, and physical contact during competitions. Biotechnology provides diagnostic and monitoring techniques that help identify physiological conditions associated with increased injury risk. By identifying potential problems early and adjusting training accordingly, athletes may reduce their risk of injury and maintain better physical health.
- *Faster Recovery*: Another important benefit of biotechnology in sports is its contribution to injury recovery and rehabilitation. Sports injuries can prevent athletes from participating in training and competitions for weeks or months. Advances in biotechnology have introduced biological treatments and regenerative medicine approaches that may support tissue repair. Their effectiveness varies depending on the injury and treatment, and some remain experimental. Biotechnology also supports improved rehabilitation through biological monitoring and individualized recovery programs.
- *Personalized Training*: Biotechnology makes it possible to develop training programs based on the biological and physiological characteristics of individual athletes. Athletes differ in their genetic makeup, metabolism, cardiovascular fitness, muscular strength, and responses to physical exercise. Through physiological testing and biochemical assessments, sports scientists can identify individual strengths and limitations. This information enables coaches to design personalized training programs that meet the specific needs of athletes. Personalized training helps athletes use their training time more effectively, avoid unnecessary physical stress, and improve performance.
- *Improved Nutrition*: Biotechnology contributes significantly to the development of sports nutrition. Proper nutrition is essential for maintaining energy levels, building muscles, supporting recovery, and promoting overall health. Biotechnology supports the production and improvement of certain nutritional ingredients, including proteins, amino acids, vitamins, and fermented food products. It helps improve nutritional strategies that contribute to athletic health and performance.
- *Early Detection*: Biotechnology provides advanced diagnostic techniques that help detect health problems before they become severe. Athletes may experience conditions such as nutritional deficiencies, hormonal disturbances, metabolic abnormalities, and cardiovascular problems. Blood tests, molecular diagnostics, and other biological assessments can provide valuable information about their health status. Early detection enables healthcare professionals to recommend suitable interventions and reduce the likelihood of complications.
- *Improved Monitoring:* Biotechnology helps sports scientists monitor important aspects of athletes' physical fitness and physiological responses to exercise. Biological measurements such as blood lactate, glucose, and selected hormonal or inflammatory markers can provide information about metabolism and physical stress. When interpreted alongside training history, performance tests, and symptoms, these measurements may help coaches and medical professionals evaluate training adaptation and recovery. Effective monitoring supports informed decisions about training intensity, recovery periods, and competition preparation.

- *Advancement of Sports Medicine*: Biotechnology has expanded opportunities for research in sports medicine and exercise science. Scientists use molecular biology, cellular research, genomics, and biochemical techniques to investigate how the human body responds to physical activity. These studies contribute to a better understanding of muscle development, energy production, tissue repair, inflammation, and exercise adaptation. Biotechnology also supports the investigation of new treatments and preventive strategies for sports-related medical conditions. Such research benefits athletes, healthcare professionals, coaches, and the broader population.
- *More Sustainable Sports:* Biotechnology contributes to safer sporting environments by improving health assessments, injury management, and scientific understanding of exercise-related risks. Better diagnostic methods can help identify athletes who require medical evaluation, while biological research can guide the development of safer training and recovery practices. Biotechnology may also contribute to environmental sustainability through the production of bio-based materials and more efficient manufacturing processes.

CHALLENGES

In spite of these benefits, biotechnology presents significant challenges. These challenges include ethical concerns, high implementation costs, health risks, genetic discrimination, regulatory difficulties, privacy issues, safety, scientific uncertainty, ethical responsibility, technological limitations, and unequal access. Other challenges of biotechnology in sports therefore include the following [2,9,13]:

- *High Cost*: A major challenge is the high cost associated with developing, implementing, and maintaining biotechnology in sports. Advanced genetic testing, molecular diagnostics, regenerative medicine, and personalized medical treatments often require specialized equipment, sophisticated laboratories, and highly trained professionals. Professional sports organizations with substantial financial resources may be able to afford these technologies, while smaller clubs, amateur athletes, and developing countries may struggle to access them. This financial inequality could create significant differences in athletic preparation, injury treatment, and recovery.
- *Ethical Concerns*: One of the most significant challenges of biotechnology in sports is the ethical controversy surrounding its application. Biotechnology can potentially alter human biological functions, raising questions about the acceptable limits of performance enhancement. The ethical concern is whether biotechnology should primarily be used to restore health and treat injuries or whether it should also be permitted to enhance athletic abilities beyond normal physiological limits. The distinction between medical treatment and performance enhancement is not always clear. Consequently, sports organizations must establish ethical principles that protect athletes while preserving fairness, honesty, and integrity in competitions.
- *Safety Risks*: The application of biotechnology in sports presents potential health and safety risks, particularly when experimental techniques are used without sufficient scientific evidence. Some biotechnology-based interventions may produce unexpected biological reactions, immune responses, infections, or long-term complications. Unproven stem cell treatments may expose athletes to infections, abnormal tissue growth, or other complications. Athletes may feel pressured to accept experimental treatments to recover quickly from injuries or maintain their competitive positions.
- *Genetic Doping*: Genetic doping represents one of the most controversial challenges of biotechnology in sports. Gene doping involves the prohibited use of genetic or cellular techniques to enhance athletic performance rather than treat legitimate medical conditions. Potential approaches could target biological pathways involved in muscle growth, oxygen transport, or endurance. Although many proposed forms of gene doping remain theoretical or experimental, their possible development raises serious concerns about fairness in competitive sports. The World Anti-Doping Agency (WADA) addresses gene and cell doping within its prohibited framework.
- *Privacy Concerns*: Biotechnology frequently involves collecting and analyzing sensitive biological information, including genetic profiles, medical histories, and physiological measurements. Such information can help sports professionals understand an athlete's health risks, recovery patterns, and possible responses to training. However, collecting genetic information raises serious concerns about privacy, confidentiality, and data security. Unauthorized access to genetic records could expose athletes to discrimination, exploitation, or reputational damage.
- *Regulation:* The rapid development of biotechnology creates regulatory difficulties for

sports governing bodies, healthcare authorities, and governments. Scientific innovation often progresses faster than the development of laws and policies needed to regulate its use. Different countries may have different standards concerning genetic testing, regenerative medicine, experimental therapies, and the protection of biological information. These differences can complicate international sporting competitions and medical practices.

- *Unequal Access*: Biotechnology may widen the gap between athletes and sporting organizations with different financial and technological resources. Wealthy professional teams can invest in advanced medical laboratories, genetic testing, specialized treatments, and personalized recovery programs. In contrast, athletes in rural communities, developing countries, and underfunded sporting institutions may have limited access to these services. This technological inequality could create competitive disadvantages unrelated to natural talent, dedication, or training quality. It may also reinforce existing inequalities between developed and developing nations.
- *Skill Shortage:* The effective application of biotechnology in sports requires professionals with specialized knowledge in genetics, molecular biology, bioinformatics, sports medicine, and biomedical engineering. However, many sports organizations lack personnel who possess the interdisciplinary expertise necessary to interpret complex biological data and apply biotechnology safely. Therefore, professional education, interdisciplinary collaboration, and continuous training are essential for responsible biotechnology adoption.
- *Pressure on Athletes*: Biotechnology may create additional psychological pressure on athletes who feel compelled to adopt advanced biological interventions to remain competitive. When some competitors gain access to sophisticated treatments or performance-related technologies, others may fear falling behind. This pressure can encourage athletes to seek experimental procedures or unproven treatments without fully understanding their risks. Sports organizations must therefore protect athletes from coercion and ensure that participation in biotechnology-based programs remains informed and voluntary.
- *Integration*: Integrating biotechnology into existing sports training and medical systems can be difficult. Traditional athletic development relies on physical conditioning, coaching experience, nutrition, psychological preparation, and performance evaluation. Biotechnology introduces additional information that may be complex, expensive, and difficult to interpret. Coaches and sports scientists must determine how biological findings can be incorporated into training programs without replacing established principles of athletic development. Successful integration requires collaboration among coaches, physicians, scientists, nutritionists, and athletes.
- *Public Trust*: Public acceptance is another challenge facing biotechnology in sports. Fans, athletes, coaches, and sporting authorities may have different opinions about the appropriate use of biological technologies. Some individuals view biotechnology as an important tool for improving athlete health and preventing injuries. Others fear that excessive technological intervention could undermine the natural abilities, personal effort, and competitive spirit traditionally associated with sports. Building public trust requires transparency, ethical oversight, scientific education, and clear distinctions between legitimate medical treatment and prohibited performance enhancement.

FUTURE OF BIOTECHNOLOGY IN SPORTS

The future of biotechnology in sports is promising as advances in genetics, molecular medicine, artificial intelligence, wearable biosensors, personalized healthcare, and biomedical engineering continue to expand scientific understanding. It has the potential to transform athletic training, performance monitoring, injury prevention, medical treatment, nutrition, and rehabilitation. One emerging direction is the integration of biological data with artificial intelligence. This integration will likely transform sports performance analysis and athlete healthcare. When combined with biotechnology, AI can help researchers interpret large quantities of biological and physiological data.

One of the most promising areas in the future of sports biotechnology is the advancement of genetic testing and personalized athletic training. In the future, improvements in genetic research may help sports scientists better understand how inherited biological characteristics interact with training and environmental factors. Wearable biosensors are expected to become more sophisticated and widely used in sports. Existing wearable technologies can measure heart rate, movement, temperature, and certain indicators of recovery. Future biosensors may provide more continuous and accurate monitoring of biochemical substances such as glucose, lactate, electrolytes, and other metabolic indicators.

Biotechnology may also contribute to the development of functional foods, improved protein sources, and scientifically formulated nutritional products [2].

CONCLUSION

Biotechnology is becoming an important component of modern sports by providing innovative approaches to athletic performance, injury prevention, rehabilitation, nutrition, and healthcare. Recent breakthroughs in biotechnology are transforming how athletes perform and recover, with cutting-edge innovations from platelet-rich plasma (PRP) therapy to mitochondrial profiling reshaping sports medicine [14]. Through advances in genetics, molecular biology, regenerative medicine, biomarker analysis, and biological diagnostics, biotechnology is expanding the possibilities for understanding and improving human physical capabilities. It also plays a crucial role in protecting the integrity of sports through advanced anti-doping technologies.

As research and technological innovation continue, biotechnology is likely to become increasingly influential in sports medicine and athletic development. The ultimate goal of biotechnology in sports should not simply be to produce stronger, faster, or more competitive athletes, but to promote healthier athletes, safer sporting environments, and sustainable human performance while preserving fairness and integrity in sports. Biotechnology is expected to play an increasingly important role in making sports safer, healthier, more competitive, and more scientifically informed. Its greatest contribution lies not merely in helping athletes achieve outstanding performances but also in protecting their health, improving their quality of life, and supporting long-term participation in sports. For more information about biotechnology in sports, one should consult the books in [6,15-19].

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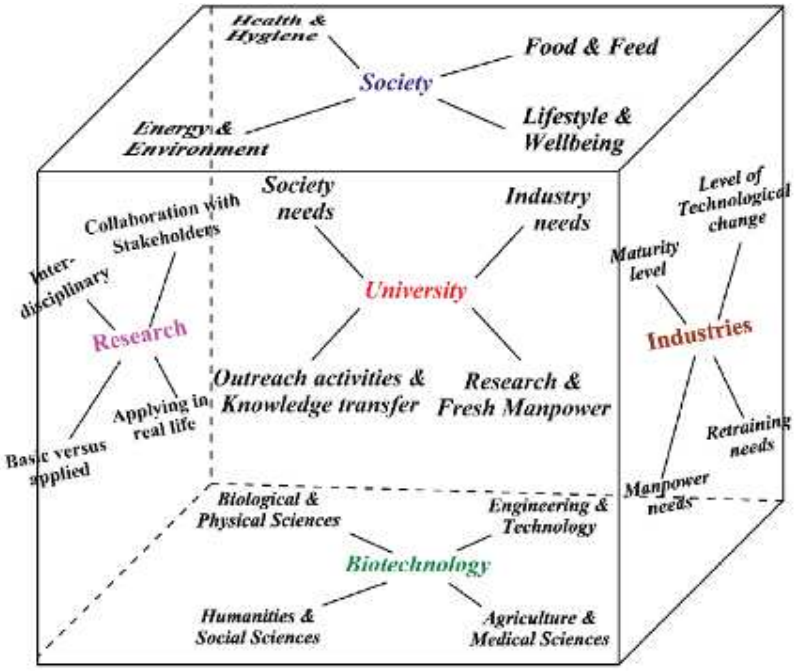


Figure 1 The multidisciplinary nature of biotechnology [1].

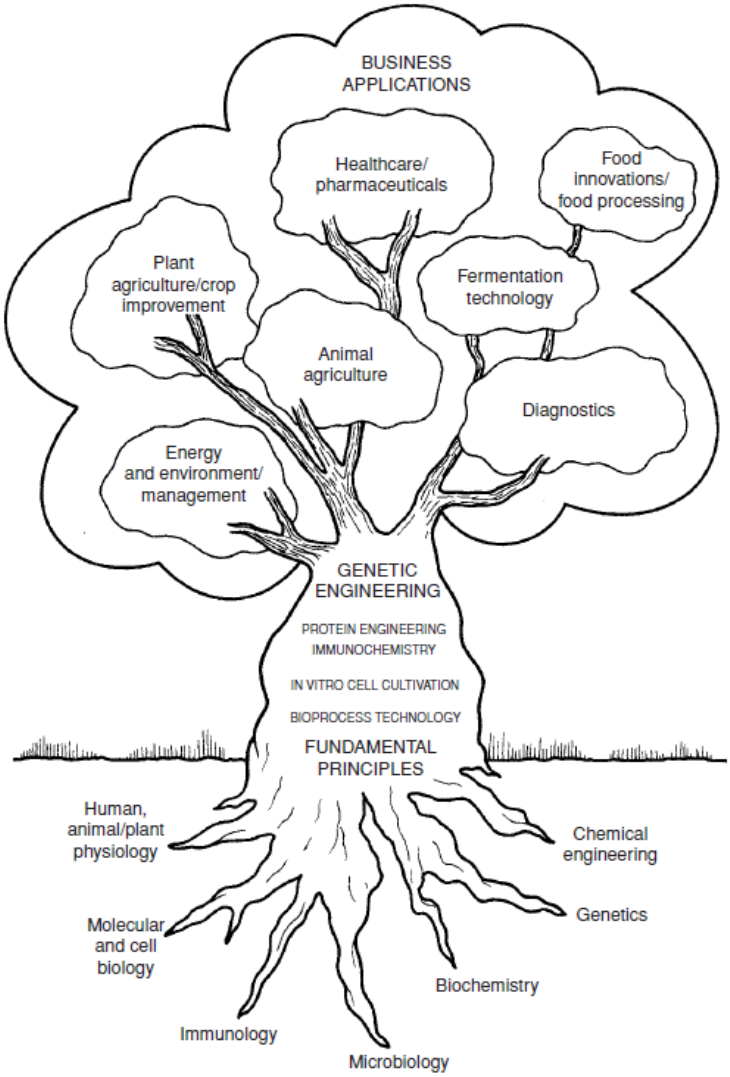


Figure 2 The biotechnology tree [6].

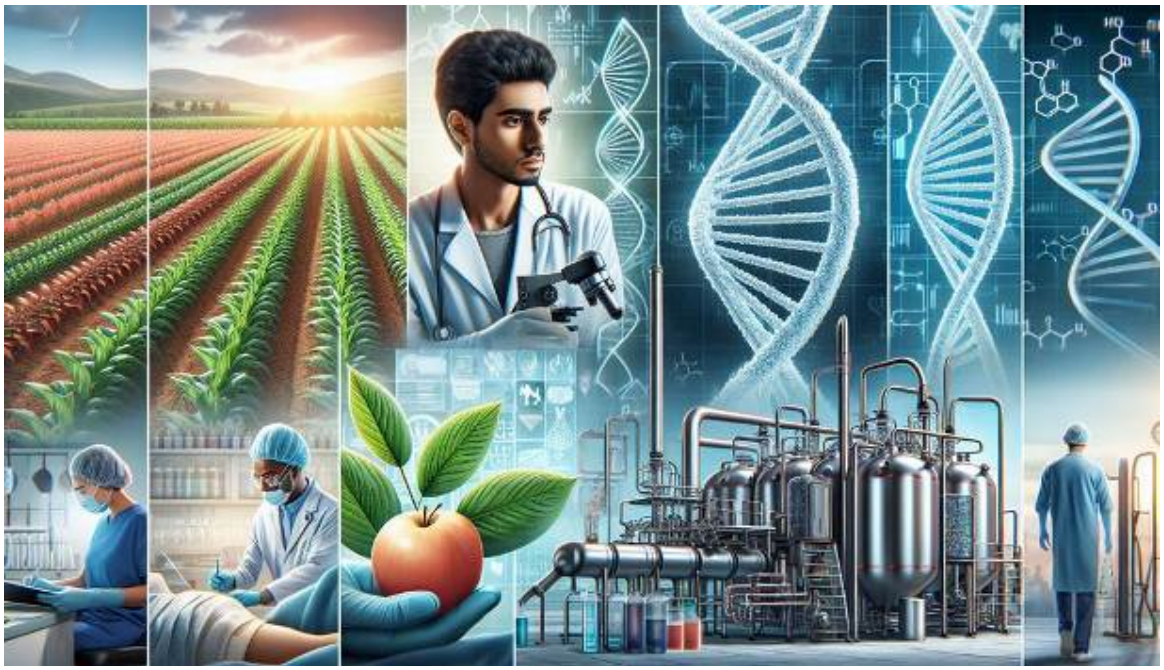


Figure 3 A representation of biotechnology [7].

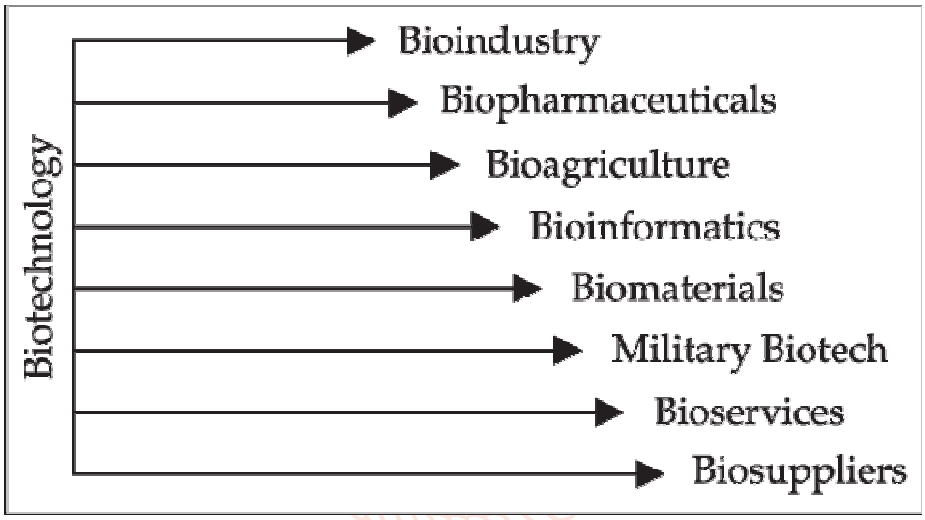


Figure 4 The classification of biotechnology sector [8].



Figure 5 Some athletes [10].



Figure 6 An injured athlete [11].



Figure 7 Laboratory equipment assisting in sports recovery research [10].

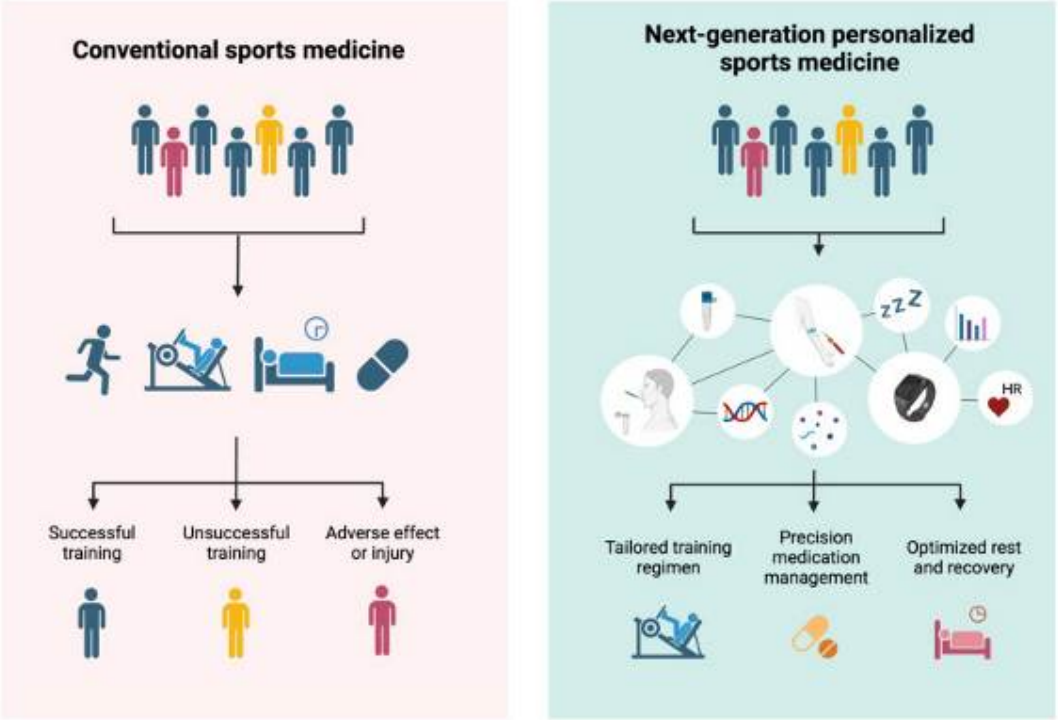


Figure 8 Comparing conventional sport medicine with personalized type [12].



Figure 9 Sports nutrition products optimized for athlete performance [10].