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Emerging Trends in Microbial Biotechnology: Applications in Healthcare and Environmental Sustainability

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Annotation: Microbial biotechnology plays a crucial role in advancing healthcare and environmental sustainability, yet gaps remain in understanding its full potential. This study explores emerging trends in microbial applications, focusing on their impact on medicine, environmental remediation, and industrial processes. Using a systematic review methodology, recent developments in microbial biotechnology were analyzed to identify key innovations and their implications. Findings reveal that genetic engineering, bioremediation, and synthetic biology significantly enhance medical treatments, waste management, and industrial production. The results highlight the growing intersection of microbiology with artificial intelligence, nanotechnology, and bioinformatics, indicating a shift toward more efficient and sustainable biotechnological solutions. These advancements underscore the need for continued research and investment in microbial applications to address global health and environmental challenges.

Keywords: Microbial biotechnology, genetic engineering, bioremediation, synthetic biology, healthcare innovation, environmental sustainability.

1. Introduction to Microbial Biotechnology

From the early days of civilization, microorganisms have been instrumental in shaping our daily lives, producing everyday essentials like bread, beer, and wine. As technology advanced, microorganisms played a major role in enabling various industrial chemicals and products. Hence, microbial biotechnology can be broadly defined as the technological application of microorganisms for the production of compounds or the development of processes useful and beneficial to humans and the environment. The technical application of microorganisms in such processes makes microbial biotechnology an interdisciplinary field, incorporating competences from biology, engineering, and technology and fostering the development of numerous cross-disciplinary methodologies. The technological application of microorganisms has greatly influenced the course of industrial reactions, processes, and products. As biotechnology matured, completely new visions and perspectives were developed, generating innovative products and processes prone to further discovery and application. Biotechnology, and microbial biotechnology in particular, is currently one of the most dynamic industries worldwide. Microbial biotechnologies have resulted in significant improvements and advancements in various industrial sectors, including genetic engineering, environmental bioremediation, livestock, agriculture, food production, brewage, textiles, and cosmetics [1]. Some of the largest improvements have powered the pharmaceutical industry, where discoveries and technological advancements have been used to develop processes for the production of potent therapeutic agents, antibiotics, hormones, vaccines, enzymes, and other useful molecules. The intercross of biotechnologies is continuously raising novel applications and visions, empowering its global relevance and fostering numerous investments in new knowledge and expertise acquisition. [2][3][4]

1.1. Definition and Scope

Microorganisms are pervasive in virtually every ecosystem on Earth. There are five major types of microorganisms: bacteria, fungi, viruses, protozoa, and algae. While the last three are of limited importance for biotechnological purposes, bacteria and fungi have been used for thousands of years for various applications. However, it has only been roughly half a century since there has been an intense interest in the technological exploitation of these microorganisms. The possibility of accentuating the production of secondary metabolites generated by fungi and furnished by microorganisms has further extended the utilization of such organisms. As a group, microorganisms occupy a pivotal position in almost all ecosystems by their ability to degrade complex organic compounds and share this capability with higher forms of life. The advent of recombinant DNA technology has helped to look beyond the realms of naturally existing microorganisms for exploiting' or with such genetic information. This has been augmented by the improvement in the methods of culture and the automation of the process [1]. This was essential as the number of microorganisms that can be conventionally isolated and grown represented a disproportionately small percentage of the existing species and maybe only the 'easy-to-grow' isolates. An enhanced version of the technology allows a genetic manipulation of any kind of microorganism and opens new vistas in exploring hitherto 'unculturable' microorganisms. The current trend in biotechnological exploitation of microorganisms tends towards the production of hybrid enzymes, new genes by recombinant means, alternative enzyme immobilization, the construction of cell factories where the entire pathway of a secondary metabolite is introduced and many more hybrid technologies [5]. Such new areas of research allow a better mixing of the academic and industrial world while offering new perspectives to operate under the given technological platform. There are two broad types of biotechnological processes: 1) those in which microbial processes are solely used in a natural ecosystem; 2) those in which 'industrial' processes are being operated and, in which microorganisms play a crucial role and others. The first mode of operation is of crucial importance in the tight management of the environment. Following the revolution of genetic engineering, a new biotechnological revolution emerged. As in the case of the first biotechnology revolution, a number of useful organisms were discovered in the environment; and again, as in the case of the first biotechnology revolution some microbes are not easily grown in laboratory conditions and represent a 'great potential'. For these reasons, the detailed knowledge of new organisms and the ecosystems they operate is difficult. An in-depth comprehension of the complexity and dynamics of natural microbial communities is a formidable task. Aspect of ethics and practicality of releasing genetically modified microorganisms into the environment is highlighted. Lastly, various technical and engineering solutions to overcome these difficulties are considered, which could propel to another high level of microbial exploitation and management. [6][7][8]

2. Microbial Biotechnology in Healthcare

Microorganisms act as versatile platforms for the development and production of a wide variety of biopharmaceuticals - therapeutic proteins, amino acids, vaccines, veterinary biologics, enzymes, and chemical building blocks - that are medically essential or beneficial to health [5]. Microbial innovations have led to considerable advances in diagnostics and personalized medicine. Conditions can be accurately diagnosed by detecting unique microbial metabolites or biomarkers present at an infectious site or specific to a disease state. Incurable conditions can be thwarted by gene-editing patients' microbiomes. Systemic infection coupled to multi-organ failure can be identified through a dedicated microbial detection tool that scans for pathogen-derived DNA in the blood stream. Therapies like therapeutic phages or bacteriophages engineered to carry lethal genes for a drug-resistant strain can profoundly impact patient outcomes [1]. Novel antimicrobial agents acting through entirely new mechanisms can selectively foster the depletion of target cell populations. In the fight against the multidrug-resistant microorganisms, microorganisms are counterparts capable of inhibiting growth of nearly all tested multidrug-resistant strains and survive hundreds of generations of in vitro exposure to them. Metabolically precise probiotic designs may mitigate numerous late-disease-state pathogenic shifts. As the consumer trend towards a health and wellness-centered lifestyle deepens, the market share and development of microbiome-focused products is expected to accelerate and expand significantly. Cultured cell products faxing immune-boosting and wound-repairing properties, developed tend to increase patient recovery rates during and after surgical operations and overall hospital stays, though microbial protective measures, are expected to make a notable debut in counterpoint pharmaceuticals where a local reprogramming of the patients' microbiome boosts probiotic therapy efficiency. The application of microbial biotechnology tools is expected to expand and diversify as conceived products pass efficacy or safety tests and tools evolve along with synchronized technological breakthroughs. Eschewing the microbial tools, contracted analytics specialists empower the consumer to make informed daily dietary choices that contribute in winning the hectic and cutthroat probiotic market forces. Editorial views are expressed on discreet choices and studies are flagged for the reader's attention, but the tone is argumentative and does not claim to represent the microbiota research community. [9][10][11]

2.1. Antibiotics and Antimicrobials

This section examines some of the latest and emerging trends within microbial biotechnology, and the ways they can be applied to help combat some of society and the globe's current and future challenges. Specifically, this could be utilized to produce the various antimicrobials vital for life – antibiotics, antifungals, anti-parasite agents, and anticancer compounds. Modern antimicrobials, as used to treat cases of infections and associated diseases, are a product of extensive research, development, and subsequent manufacturing base, primarily utilizing microbial biotechnology. Microbial antibiotic (secondary metabolite) production, in particular, has developed as a critical component of microbial biotechnology, both from naturally existing microorganisms and through genetic engineering of such species. Outside health applications, microbial biotechnology may provide numerous other benefits in monitoring health and diagnostics. This specific subsection investigates antibiotics and other antimicrobials that are developed using microbial biotechnology and other technologies associated with genetic engineering or are long established and used in biotechnology along with some newer advancements. Then an examination is done of several "new" developments within this important area of microbial biotechnology, all largely driven by emerging trends in science and technology. The role of microbes (bacteria and fungi) in the discovery and development of modern-day antibiotics is expansive and somewhat overshadowed by, more 'glamorous' and, for the pharmaceutical industry, financially rewarding sources. Mitomycin, streptothricins, viomycin, mupirocin, polymyxin, and platensimycin are some examples of antibiotics developed from non-fermentative bacteria or actinobacteria. In contrast, the natural product origins of most clinically approved antibiotics trace back to microbial fermentations [1].

3. Microbial Biotechnology in Environmental Sustainability

The emergence of ecology as a major scientific discipline has familiarized us with the trophic level in an ecosystem, opening up the first opportunity for us to conceive the potential risks of overexploitation directly brought about by the abuse of chemical biocides to affect non-target organisms, leading also to a failure in arthropod pest control. Soils and oceans as global pools of microorganisms constitute the core of the album of life, metabolism, and energy production necessary for the persistence of essential biogeochemical cycles. Since the industrial revolution, increased pollution has changed the exposure scenario of soil in terms of the number and concentration of contaminants. Polluted sites are generally too large, distant, or complex to be directly treatable through physical or chemical technologies. The continuous advancement and the unrivaled performance of cutting-edge analytical tools are boosting a rapid and deep understanding of biological mechanisms.

Any biotechnology that can provide new insights and/or product/process-related improvements in mycoremediation or will enhance a future better implementation should rely on modern molecular biology and offer a genomics-based approach. A wise combination of genetics and bioprocess optimization was successfully employed to improve the mycoremediation of contaminated soils. Genetic manipulation of microorganisms tailored to degrade specific recalcitrant contaminants, the overexpression of key enzymes or degradation pathways, the manipulations of catabolic genes directly responsive to contaminants, enhancing the bioavailability of contaminants, promoting mycosurfactant production and transport, or the production of biosurfactants involved in the remediation of both LNAPLs and DNAPLs, were successfully used. The use of genetically engineered white rot fungi to enhance the in situ bioremediation of soils contaminated with high molecular-weight PAHs are presented and several case studies focusing on the effectiveness of WRF-based in situ systems to clean up soil and water contaminated with different types of recalcitrant pollutants are also described. [12][13][14]

3.1. Bioremediation

Bioremediation is a crucial application of microbial biotechnology in the field of environmental sciences. Bioremediation is a process by which microorganisms, including bacteria, fungi, yeast, and algae, are used to degrade organic and inorganic pollutants in the contaminated sites, into less toxic forms through biological or enzymatic activities. Polycyclic aromatic hydrocarbons (PAHs), heavy metals, hydrocarbons, pesticides, and plastic wastes are some of the pollutants that contaminate the soil, air, and water. Streams, lakes, ponds, rivers, and oceans get polluted by physical, chemical, and biological pollutants. Inability to manage and treat these pollutants can lead to the destruction of the ecosystem and also loss of plant, animal, bird, and marine life. Contamination of drinking water leads to different waterborne diseases, skin diseases, cancer, and death of living organisms. These can be prevented and treated by the biological methods using eco-friendly bacteria, fungi, yeast, and algae [15]. There are in-situ and ex-situ bioremediation techniques applied in the bioremediation of contaminated sites. Biostimulation, bioaugmentation, biosparging, bioventing, composting, land farming, and phytoremediation are some of the techniques applied in the bioremediation of contaminants from metals, forests, crops, soil, and water resources. Different bioremediation methods are applied for the treatment of physical, chemical, and biological pollutants. Methodologies also developed for the estimation of biodegradable and non-biodegradable pollutants in the contaminated sites. Recently, [16] have developed a mathematical model for the bioremediation of heavy metals in the soil and water ecosystem. Heavy metal effluents produced from pharmaceutical, petrochemical, chemical, and fertilizers industries are treated by using eco-friendly bacteria and yeasts at a different pH and temperature ranges. Bioaccumulation and biosorption techniques also applied to remove the heavy metals from the contaminated sites. Estimation methodologies are in progress to estimate the capacity of the metalloresistant bacteria toward the biosorption of Cr(VI), Cu(II), Zn(II), and Ni(II) heavy metal effluents. Only 2% of the biosorption capacity of the metalloresistant bacteria is effectively utilized for the removal of the heavy metals in the contaminated sites. Future prospects, challenges, and limitations in the bioremediation of heavy metals from the contaminated sites are analyzed. Heavy metals effluents are uncontrollably disposed of into the streams, rivers, lakes, and oceans, it gets accumulated in the liver, kidney, and spleen of human beings and causes several diseases like skin diseases, cancer, mental disorder, and death of human beings. So, treating and managing the heavy metals in the contaminated sites are crucial for a sustainable naturopathic living environment. [17][18][19]

4. Genetic Engineering and Synthetic Biology

The ability to manipulate the genomes of microorganisms has advanced in recent decades, enabling scientists to introduce new genes, augment cellular processes, or otherwise re-engineer cells for beneficial characteristics. Scientists have discovered methods for manipulating DNA and RNA within cells, leading to a field known as genetic engineering. Fundamental techniques include culturing and isolating individual genes, synthesizing DNA molecules, constructing plasmids, targeting genes for replication and expression, creating genetic markers, and identifying organisms in which genetic material can be inserted and expressed [1]. Applications of genetic engineering to microbes include the mass production of peptides, proteins, hormones, enzymes, biofuels, and antibiotics and the creation of genetically modified organisms for environmental cleanup and crop protection. Genetic manipulation of microbial matter is poised to revolutionize industries and become a hallmark of the biotechnological landscape. In recent decades, the manipulation of DNA and RNA has become routine for modifying and producing beneficial traits in organisms. Such traits are customizable and can be suited for applications in numerous industries, such as food, textiles, and health. Two notable developments in this field are the industrial ventures of genetic engineering and the maturation of synthetic biology. The latter is defined by the principles of designing and constructing new biological parts, devices, and systems, and refers to ensembles of genes that function independently from the organism’s chromosome. As knowledge of genomics grows, this permits genetic circuits to be economically produced. Such capabilities are expected to redefine biotechnology practice over the coming years and will result in advancements in medicine, agriculture, energy, environmental care, and industry.

4.1. CRISPR-Cas9 Technology

Since the first reporting in the field of microbial biotechnology, it conforms to its promise of gene editing with high efficiency and precision. Its accurate mode of editing contributes to the development and prosperity of the microbial biotechnology, in addition, to the leapfrog development in medical and agricultural application. Therefore, this technology is undoubtedly regarded as the monumental milestone in the microbial biotechnology and gene editing. Over the past years, gene editing, a practice of insertion, deletion or modification of nucleotide, on the basis of prior manipulatable knowledge, has been a focus of many scientific researches [20]. However, it is not a piece of cake to achieve this goal. For the general common conventional methods, including homologous recombination, group II introns, Zinc Finger Nuclease (ZFN) and Transcription Activator-Like Effector Nuclease (TALEN), the process of gene editing is not only time-consuming and arduous because of the low efficiency, but also appears to be a notable challenge due to its cumbersome operability. However, when it comes to the CRISPR-Cas9, a new cutting-edge technology, thrilled to be observed, such difficulties seem dissolved effortlessly, and the goal of gene editing is as simple as eating pies. With the widely spreading of the CRISPR-Cas9 in the microbial-biotechnological community, a series of advanced made to order with high standards as well as the final consummation of outsized project are adept to be fulfilled. Sparking the application of CRISPR-Cas9 in the control of the microbial populations mainly as the bioremediation and biodegradation of recalcitrant compounds and the application in the biopharmaceutical spheres. With a surged interest in the “microbiome”, a comprehensive study refers to the distinct amount of sheds light on the new capacity of the utilization of the CRISPR, not only for the prediction of the behavior and interactions in the microbial society, but also contributes to the modulations and workings of the microbial society with the final boost of the outcome of the biomedic commitment. [21][22][23]

5. Nanotechnology in Microbial Biotechnology

Nanotechnology is currently intersecting with microbial biotechnology, offering a unique platform for innovation. Nanoparticles have great potential in enhancing the functionality and applications of microbes. Recent advances in nanotechnology and nanobiotechnology have led to the development of nanomaterials with unique structures, properties, characteristics, and applications in diverse areas. The miniaturization of physical and chemical properties of materials at the nanoscale makes them very different from bulk materials and causes them to interact uniquely with various molecules, cells, and biological systems. A broad range of metallic, polymeric, ceramic, and nanocomposite nanoparticles are used in various applications of bioengineering. In this respect engineered microbe-assisted drug delivery system for targeted therapy development by the integration of nanotechnology into microbial biotechnology is discussed in detail. Addition of various metallic, polymeric, and other inorganic nanoparticles can enhance the functions and applications of microorganisms, though the safe utilization and uncontrollable release of these particles could be toxic to human health and the environment.

Microbes are naturally capable of synthesizing nano-sized materials, including nanoparticles and nanostructures, while utilizing the secondary metabolites they produce in the biogenesis is one way to control the shape and size of nanoparticles. Therefore, the natural metabolites of bacteria and fungi are used in the colon and control the synthesis of nanoparticles inside the producer microorganisms. The nanoparticles were used as enzymes and chemicals in the sphere of application of nanoparticles as well as in various other advances in biological action. Biomedical applications in connection with nanoparticles have been summarized and planned for the upcoming advances and future goals in nanoparticles. Biosensing using nanoparticles for the detection of heavy metals has been addressed which provides improved outcomes. There are several other advantages to the utilization of metallic nanoparticles for the elimination of toxic waste from pharmaceutical, industrial, textile, and agricultural water bodies. Common challenges in utilizing microbial biosynthesized nanoparticles in different applications field and current procedure to tackle these challenges has been discussed in brief. Industries and regulators of the composition of several nanomaterials have shown a concern about their use in a risky way. The use and management of polypyrrole nanoparticles in a controlled drag release system in agriculture intended to improve edible products of well-being are reviewed, as are their surface handling methods. [24][25][26]

5.1. Nanoparticles in Targeted Drug Delivery

Active targeted drug delivery plays an important role in improving or facilitating the therapeutic efficacy of drug molecules. An ideal active targeted drug delivery is designed to interact with specific vectors in a controllable manner by direction, magnitude, timing, and context. The recent development of nanotechnology has presented the design of nano-carried targeted drug delivery, offering unique advantages over traditional micro-particle drug delivery. However, nanotechnologies have only just been widely recognized as up-and-coming and innovative. The significant improvement on interaction among active targeted nanocarriers, microorganisms, and vectors may further expand the opportunity and potential of targeted drug delivery. The interactions drive various drug nano-carriers unique advancements or strategies to enhance the efficiency and efficacy of treatment. In light of improvements in knowledge and methodology, investigations on active targeted drug delivery nanotechnologies with microorganisms may revolutionarily influence advanced approaches as well as clinical trials on treatment of drug carries. This mini review delivers cutting-edge reports on this systemic concept, relevant investigations dealing with it, the design of nano-drug bowls to provide ideas for new researches, and beneficial strategies. Also, an additional opportunity and discussion for targeted therapy delivery of other cargo to microorganisms is proposed.

6. Bioinformatics and Big Data in Microbial Biotechnology

Bioinformatics and Big Data are expected to greatly advance microbial biotechnology in the coming decade. Innovative computational tools and algorithms will be crucial to analyze vast datasets from research on individual microbial strains to those in complex communities. These sets of genomic data are ever growing and thanks to plummeting sequencing costs will be a prominent basis for biotechnological applications [27]. Computational approaches have taken strides over the past few years to deal with these data, to perform de novo assembly, genome annotation, and to predict gene functions even under condition of strong gene paralogy. However, further development and optimization is needed to make sure further deployment of the wealth of microbial genomics. This will encompass models and software for rapid and accurate gene functional annotation, as well as ever more integrative approaches to predict metabolite production, metabolic interactions, and phenotypes from genome sequences. Bioinformatics is also crucial to retrieve, process, and integrate data from other diverse sources such as metagenomics, metatranscriptomics, and transcriptomics, that are becoming increasingly important in microbial biotechnology by letting to prototype devices, make bioprocesses more sustainable, and to discover processes, in multifarious environments [28]. Big data analytics can infer novel genotypic and phenotypic features of organisms, and hence be of help in the development of microbial isolates and design novel strains. Current progress and future developments are exemplified by a series of applications in biotechnologically relevant model organisms. However, they also highlight concerns that should be addressed to improve uptake of novel data-driven approaches in microbial biotechnology, such as pan-genome-wide association studies and rules on the responsible and confidential use of proprietary data.

6.1. Computational Tools for Genome Editing

There is a multitude of software programs and algorithms available to design complicated genome editing strategies. With the advent of CRISPR/Cas9 systems, a variety of design tools are developed to design CRISPR guides. Some design tools offer more complicated aspects compared with others. For example, one tool increased predictability of off-target effects and reduced the number of sgRNAs that did not work experimentally. More advanced tools predict off-target effects and enhance precise gene editing. Another tool uses a web tool to predict off-target effects efficiently using up to 48 target sequences. Guidescan tools design paired gRNAs against Cas9 by selecting gRNAs with the fewest off-target effects. Another tool designs target-directed base editors to introduce precise point mutations using cytidine deaminase and adenine deaminase. To narrow down a list of CRISPR targets in microbes, some tools naturally select informative and conserved targets.

Current difficulties are accompanied by brand new opportunities. The increasing capacity of parallel computing could significantly contribute to research in biotechnology by dealing with growing data complexity. Unimaginable combinations of simulated conditions are possible using computational models. The rise of systems biology accelerates the integration of genomic, post-genomic, metabolomic, and fluxomic data. However, even the most advanced software is not a complete solution for any issue. Pre-existing knowledge of the analyzed system and computational tools must be combined. Whatever was designed, every predicted and experimental result should be carefully analyzed and corrected if necessary. Thus, a match between computational and experimental biologists is essential to develop any successful project. Up to now, the usage of computational tools was presented using model case studies and revealing hints on their soundness and importance to progress in microbial biotechnology. [29][30][31]

7. Regulatory and Ethical Considerations in Microbial Biotechnology

7. Regulatory and Ethical Considerations

Critical to the responsible advancement of any scientific research and commercial activities based upon it, are the regulatory and ethical considerations from the outset. Since the advent of recombinant DNA and the results of some spectacular ethical failures of high-profile applications a generation ago, the regulatory environment governing the use of genetically manipulated microorganisms in research and industry has steadily and incrementally increased [32]. The result is a framework of multifaceted regulatory bodies and guidelines that vary from country to country, but broadly protect an extensive Declared List of Pathogens from genetic manipulation. The possible risks associated with genetic manipulations involving organisms not on this list, and ones made more potent, virulent or wider in host range due to the manipulations, are assessed, and every project requires justification of why the manipulations are necessary and what measures will be taken to minimise the risks. Furthermore, gene synthesis companies prompting further fears that this could be circumvented, resulting in a self-enforced code of ethics not to synthesise gene of certain sequences, while most select agent sequences do not over-ride public health or scientific exemptions, and can trigger even closer scrutiny of applications. The publication of specific experiment details can, in some cases, also pose risks if it allows replication of otherwise unpublished results, and several countries have established direct relationships between their select agents lists and what details scientists are allowed to publish. This changes periodically and can happen suddenly. The full contents of select agents lists are not made public, to evade arsonists or terrorists, leading to occasional prosecution of newspapers are publishing lists prior to official release, and physical shipment of bacterial stocks is also affected where henipah virus, for example, can only be shipped by innoculation into living animals. Public engagement must account for concerns more broadly. Public engagement is also about how much the public is informed about use of GM organisms, and ensuring a certain transparency in the overall political process. Drawing the line between fair game and sensitive information is intriguingly a wider political problem, as the perfect prosecution of whistleblowers exemplifies. The management behind the regulation of biotechnology and plant varieties should encourage and ensure a level platform for debate between the needs of industry and the general public rather than employ regulatory bodies as a form of putty in the hands of industry, or changes its composition according to political expediency, as in the UK. The multidimensional nexus of regulations surrounding the use of genetically manipulated microorganisms presents a significant barrier to new market entrants, and is a motivational vector directing activity away from both certain difficult to handle organisms, and some high potential value applications with a strong risk probabilities. Conversely, the gradual harmonisation of regulations across borders can open fields for particular innovations, or in the domain of tissue culture biotechnology. Such a drive towards harmonisation is a pro-active force in shaping the ethical and public welfare concerns which play a principle role in guiding the development and implementation of the regulatory regimes in the first place.

7.1. Global Regulations

There are an increasing number of pharmaceutical and consumer health products on the worldwide market that are based on or involve microorganisms as a product or production platform. These products are derived from biotechnological procedures, such as recombinant strains that are produced with classical industrial fermentation techniques, from invasive use of naturally occurring microorganisms or products derived from them, or from non-obvious use of microorganisms, e.g. in clinical applications or gene therapies. Exogenous and endogenous organisms may be used. The use of such organisms can be expected to grow, particularly in light of the new application of next generation DNA sequencing to more traditional taxonomic collections given recent global efforts to create such global collections. There will be increased refining of natural products appearing on the market, with associated intellectual property (IP) rights, and the enhancement of fermentation platforms. In turn, large-scale fermentation can have huge environmental impacts. It will be important to develop a coherent strategy among the relevant stakeholders on the worldwide level in order to foster the growth of such biologically derived products, ensure that as far as is possible the manufacture and transport of components is sustainable, and address so far largely unaddressed equitable and access and benefit sharing (ABS) issues. Species of unicellular morphologies are important, and relevant genetic modifications can be both straightforward and extremely useful in trait selection. Microbiological products with new features will emerge from these recent achievements. These recent discoveries are materializing in products that enter a market heavily regulated, and are affecting all areas from technical details of manufacturing protocols to ethical issues. International alignments should be sought to harmonize and make the regulatory path simpler [33].

8. Commercialization and Industry Trends

8.1. Startups and Innovation Hubs

Innocentive is a global company that connects some of the world's leading companies to problem solvers, like talented individuals, companies, and organizations of any size to answer important questions for successful business outcomes. BioCrossroads in Indianapolis serves as a catalyst for further developments in Indiana's historically strong life sciences industry by connecting companies, academic and government organizations, and businesses to facilitate research projects as well as gather resources to attract and develop innovative technologies for new businesses in Indiana. Such initiatives and hubs are growing in number in various countries as the biological sciences continue to innovate and initiate new revolutionary technologies. In South Africa, the Department of Science and Technology's innovation hub development program is actively promoting the development and growth of innovation hubs, and rural, mobile, and satellite innovation hubs are initiated to stimulate local innovation capacity and resources. In fact, the department started capital recording of an additional six new hubs for high-tech sectors in various other parts of the country, with initiatives to foster increased growth in each of the other provinces in the next financial year.

9. Future Directions and Emerging Technologies

Recent years have seen an explosive growth in the field of microbial biotechnology, an interdisciplinary area that encompasses the exploitation of microbes for the welfare of human society. The field dates back to the early days of the discovery of microorganisms when Antony van Leeuwenhoek observed the first microbes through a simple optical lens, leading to the development of vaccination by Edward Jenner. However, the rapid growth of the field is mainly due to the discovery of the microorganisms responsible for the industrial production of antibiotics, useful recombinant proteins, and bioactive natural products. Microbial biotechnology has emerged as a powerful tool for the production of numerous novel natural bioactive compounds that have been used in diverse sectors. It is now a multi-billion-dollar industry whose share in the global economy continues to increase at an exponential rate.

A flourishing area within microbial biotechnology is the bioprospecting of various biomes for novel and diverse bioactive natural products. However, it underlies the need for continuous research to maximize the potential that God has given. A few substances owe their origin to the research on chemical synthesis ; still, most of the compounds are developed through biology search, either by studying natural products in the native source or by isolation of the metabolome, transcriptome, and the genome of unculturable microbes, a fact that propels the need into the scientific research of “Life Sciences” [1]. Random screening has always been the classical approach to the search for biologically active compounds. Hence, the discovery of new novel natural bioactive compounds will drive the economy of both developing and developed nations. Indeed, recent advancements in other disciplines have influenced microbial biotechnology. Bioinformatics offers unique insights into the exploration of the vast repertoire of genes found in a microorganism. Analogously, it also constitutes an attractive method for cloning and expression studies of unexplored metagenomes [5]. Generally, 90% of the available antibiotics on the market are originated either from natural products produced by microbes or are their semi-synthetic derivatives. But the way of discipline needs to be followed to safeguard the world’s microbiota, while searching for novel natural bioactive compounds. Future directions in the world of microbial biotechnology, emerging commercial interests, and the importance for health and environmental management are elucidated.

9.1. Artificial Intelligence in Microbial Biotechnology

Advancements in technology over the last decade have transformed many industries including microbial biotechnology. One notable area of advancement is the integration of artificial intelligence (AI) with microbial biotechnology. Artificial intelligence (AI) has the capability to fundamentally transform microbial biotechnology in the same way that it has changed the way the internet is searched or products are purchased. The massive amounts of data obtained in microbial research is enhanced greatly by AI, from analysis and pattern recognition through to development of innovative predictive models. Machine learning based algorithms are being widely adopted in the optimization of microbial processes and the design of products. This brings almost unparalleled precision to a new competition and optimization regime. These techniques are used in a wide variety of products including monoclonal antibodies for cancer treatment. They are also being used to study the structure of proteins, something that was once considered impossible. Microbial biotechnology has a core role to play in the sustainability of the planet and processes including recycling, carbon reduction and greening can all be improved through AI implementations.

The interaction between AI and microbial biotechnology identifies the benefits and considerations of AI implementation in the field. Case studies demonstrate the wide variety of applications, from identifying regions of the genome that improve the production profiles of bacteria from drug production, through to exhaustive learning of the metabolic networks within cells. There is also an ethical aspect that work in AI and microbial biotechnology should be collaborative to maximize benefits, with biotechnologists creating better access to relevant data and asking the right questions for the development of AI, rather than companies outsourcing a problem to a black-box model, which may be difficult to interpret. Addressing and overcoming some of the considerations for the field are suggested, such as the awareness of data privacy, algorithm transparency, and copycat products. Also discussed are the concerns regarding the over-hyping of AI and the need for promoters to be realistic about its capabilities and timescales [34].

10. Conclusion

Microorganisms play key roles in health as well as environmental and economic sustainability, affecting ecosystems, agriculture, and economies worldwide. Our health is inseparably linked to a rabble of microorganisms evolving with us over millennia. In bodily regions, microorganisms are essential for the whole metabolic system, digestive tract, and protection against disease. Despite the critical function of microorganisms, enormous sectors of microbial activities are still unidentified and therefore still have huge potential to shape the global economy. Microbial biotechnology, based on microbes and their components, processes, or metabolic products, has a pivotal role in industry pursuing their application to human welfare. Emerging research and engineering of microbial processes dramatically extend the existing horizons empowering innovation in bioprocess engineering, business models, raw materials, and products. In prior decades, specific ingredients derived from microorganisms were universally obtained directly from the environmental sources of the microorganisms, which led to over-harvesting, desertification, and the loss of indigenous knowledge. Today, the important bioactive ingredients appear increasingly to be obtained from microbially derived processes, and the biotechnology and pharma industries are adopting microbial processes to provide these natural ingredients. A looming health challenge is that many cultural habits, especially in Europe and North America, are characterized by the extensive use of antibiotics, resulting in depleted and less effective treatments. Antibiotics are potent microbial pesticides, but they are also potent stress factors driving microbial community transitions. Biotechnologists are however already engineering microbial technologies that will foster microbiomes that are less sensitive to such stress, in the hope that developing such reservoirs of resilience will protect patient microbiota from unintended collateral damage. Generally speaking, the cheaper, ‘low tech’ field is the most prone to unrealistic optimism and overhyped promises, while at the other extreme, stringent regulation will hinder the faster development of such empowering technologies. The authorities need to be educated about the systems properties of microbiomes and become confident innovators in governance promoting rather than hindering innovation.

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