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Advancements in Synthetic Biology for The Development of Innovative Laboratory Diagnostic Tools: A Comprehensive Review

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Abstract

Background: Synthetic biology has emerged as a transformative field with the potential to address global challenges in health, sustainability, and resource accessibility. This review explores the advancements in synthetic biology aimed at developing new laboratory diagnostic tools. We analyze the methodologies employed in both cell-based and cell-free systems, emphasizing their applicability in diverse environments, including resource-limited and off-the-grid settings.

Methods: The review synthesizes findings from recent studies demonstrating the successful implementation of synthetic biology techniques in real-world scenarios, such as bioproduction, biosensing, and therapeutic delivery.

Results: Results indicate that while whole-cell platforms offer advantages in mass production and complexity, cell-free systems provide enhanced stability and flexibility for rapid diagnostics. However, both approaches face significant challenges, including genetic stability, resource requirements, and operational complexity. The review highlights the necessity of interdisciplinary approaches to overcome these obstacles and improve the robustness and usability of synthetic biology applications.

Conclusion: Ultimately, we conclude that continued innovation in synthetic biology can lead to the creation of effective diagnostic tools that are not only responsive to immediate medical needs but also sustainable for future applications in remote and resource-limited contexts.

Keywords: Synthetic biology, diagnostic tools, cell-based systems, cell-free systems, bioproduction.

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1. Introduction

Synthetic biology and its applications provide significant potential for meeting global humanitarian needs, including sustainable development objectives, zero hunger, health and well-being, decreased inequality, and enhanced access to sustainably produced commodities and services [1]. Recent advancements have illustrated the capacity of synthetic biology to transform technologies across various applications, including biocomputing, living materials, electronic interfacing, therapeutic genome editing, multiplexed diagnostics, cellular recording, third-generation biorefineries, and living biotherapeutics [2,3]. The most readily acknowledged and sophisticated use of synthetic biology is the modification of metabolism to generate high-value products for uses like biofuels, natural plant products, polymer precursors, and bio-inspired materials. The capacity to convert microbes into chemical factories that rival organic chemical synthesis is heralding a new epoch in biomanufacturing [4].

Notwithstanding these significant advancements, the majority of contemporary breakthroughs are not readily applicable to real-world environments, which are somewhat different and changeable in contrast to the controlled circumstances present in laboratory settings [5-8]. We propose that external laboratory scenarios consist of three primary contexts for resource availability: resource-accessible, resource-limited, and off-the-grid. Resource-accessible environments include scenarios in which technology is used with almost unrestricted access to resources and skilled humans. Such scenarios, exemplified by large-scale industrial biotechnology environments, often include the transfer of laboratory-scale outcomes, followed by repeated process optimizations, scale-up, and cycles of biological redesign. Nonetheless, effective deployment, even under optimal resource circumstances, is not certain because to several variables such as genetic stability, economic considerations, practicality, and other technological hurdles [9-12]. Resource-limited settings refer to situations characterized by the use of technology in more isolated environments, which have restricted (although not nonexistent) access to resources and/or knowledge, such as distant military and space operations. Extreme conditions in off-the-grid environments include scenarios with limited or absent access to resources, electrical power, communication infrastructure, and expertise, including deployments in remote regions of the Earth or inside the gut microbiota. These applications require that deployed technology function independently without external resources or involvement [13-15].

In contrast to the relatively straightforward technology transfer and scale-up considerations usually required in resource-accessible environments, resource-limited and off-the-grid contexts need innovative synthetic biology paradigms for effective implementation. These applications include stringent criteria, including a high degree of system flexibility, long-term storage capabilities, intermittent or recurring use, and the capacity to function with little equipment and involvement [16]. Numerous significant obstacles and scientific prerequisites for implementing synthetic biology-based technologies in prominent extralaboratory environments. For success, external laboratory platforms must exhibit genetic and functional stability over extended durations under diverse storage circumstances, need minimum equipment and resources for operation, and demand little intervention from skilled specialists. Synthetic biology is experiencing a paradigm shift from the use of biology to its deployment [17-19].

Both cell-based and cell-free system methodologies have distinct benefits and obstacles for their use in extralaboratory environments. Whole-cell platforms are generally more amenable to mass production and the integration of multiple complex assays or reactions; however, they face challenges related to long-term viability and stability, toxicity of analytes or reaction components, and delays stemming from the necessity of cell growth and analyte/nutrient transport [20,21]. Cell-free platforms may mitigate several related issues by eliminating the need for living cells, hence enabling the detection or production of chemicals that are generally hazardous to cells. This characteristic of an open reaction environment enables the modulation of metabolism, transcription, and translation, for example, by the exogenous introduction of non-native substrates [22]. The removal of the need to maintain life allows for the exclusive concentration of the system's resource allocation on a certain product or reaction of interest. Nonetheless, considerable diversity across batches has been observed among academic laboratories regarding cell-free protein synthesis outputs. Moreover, the brief durations of cell-free reactions (generally lasting hours), elevated reagent expenses (notably for energy sources and nucleotides), and challenges in folding intricate protein products impose constraints on the applicability of cell-free platforms [23-26].

This Perspective emphasizes three primary application domains for the external deployment of synthetic biology: bioproduction, biosensing, and closed-loop delivery of living therapeutics and probiotics. Each major section commences with a succinct introduction regarding its relevance to external applications, examines current endeavors in that domain, addresses areas necessitating further enhancement for external deployment, and concludes with potential scenarios for the applicability of external technology.

2. Manufacturing in distant and unconventional settings

Synthetic biology has initiated the capability for both on-demand and continuous (or responsive) manufacture of biochemicals, medicines, and even food or food components using various host species. The advancements in synthetic biology that enhance the commercial manufacturing of small molecules have been well documented in other sources [27]. Conversely, insufficient focus has been directed towards production technologies suitable for extralaboratory contexts, including the on-demand synthesis of small molecules and proteins in developing countries, during remote military and space operations, or for other in situ production applications within built environments [28-30]. In acknowledgment of the challenges inherent in bioproduction outside laboratory settings, several funding initiatives have been launched, including the DARPA Battlefield Medicine program, which seeks to address barriers to on-demand manufacturing via the Pharmacy on Demand (PoD) and Biologically Derived Medicines on Demand (Bio-MOD) initiatives. Moreover, NASA's Translational Research Institute for Space Health (TRISH) aims to enhance astronaut health and performance during space missions, including the on-demand production of therapeutics aboard spacecraft [31].

Initiatives using both whole-cell and cell-free technologies, with collaborative advancements in material science, have provided proof-of-concept studies for molecular manufacturing applications outside laboratory settings. Fundamentally, on-demand and continuous production capabilities include the preservation and maintenance of metabolic activity across many environments. This necessitates that field-deployable platforms exhibit genetic and environmental stability over both prolonged storage and active metabolic conditions. Moreover, the integration of improved platform stability with intuitive deployment technologies (including integrated production and purification modules and liquid handling capabilities) is essential for implementation in environments with restricted or absent resources or skilled staff [15,20].

3. Whole-cell manufacturing systems

Conventional cell-based recombinant production systems have been the principal method for manufacturing protein therapies since the introduction of recombinant insulin in 1982 and remain used for the creation of active pharmacological components. Nonetheless, the dependence on Chinese Hamster Ovary (CHO) cell platforms for production presents challenges for the establishment of rapid and shelf-stable on-demand production systems, due to the inadequate viability of mammalian cells after rigorous preservation methods like freeze-drying, as well as significantly slower biomass accumulation relative to alternative hosts such as yeast [30]. The failure to uphold cold-chain standards demands the development of small-scale, portable drug manufacture systems to enhance access to essential pharmaceuticals. Consequently, several organizations have adopted the methylotrophic yeast *Pichia pastoris* (*Komagataella phaffii*) for applications outside the laboratory, since this host necessitates fewer complex conditions and reduced processing durations for recombinant protein synthesis, along with its resilience to freeze-drying. *P. pastoris* is the preferred host for the synthesis of complex recombinant proteins compared to simpler hosts like E. Escherichia coli and Staphylococcus. Cerevisiae is suitable for producing products, including protein therapies, that possess mammalian glycosylation patterns. Moreover, large-scale fermentation is not preferred for rapid implementation [31].

Perez-Pinera et al. [32] have modified *P. pastoris* for the inducible and switchable production of two separate biologics (rHGH and IFNα2b), optimized for a milliliter-scale, table-top microfluidic reactor that can produce single-dose quantities within 24 hours. This exceptional production of two separate biopharmaceuticals underscores a method for enhancing production efficiency by using the same biomass for various products, while also exemplifying the reduced reactor footprint required for the synthesis of complicated proteins. The incorporation of supplementary orthogonal genetic circuits in such platforms could facilitate the multiplexed synthesis of a diverse range of therapeutic compounds, which could be modulated in response to specific stimuli, potentially culminating in an integrated diagnostic and therapeutic production system. This increased production flexibility may prove particularly advantageous in scenarios such as space missions or active military operations, where fluctuating demand for various therapeutics coincides with restricted capacity for transporting production units assigned to singular

products. Crowell et al. [33] have developed the InSCyT (Integrated Scalable Cyto-Technology) platform to overcome certain field-deployable limitations of on-demand platforms, such as expression constraints and downstream separations. This automated, cell-based, table-top multiproduct biomanufacturing system can achieve end-to-end production of hundreds to thousands of doses in approximately three days, contingent upon the therapeutic compound. This platform facilitates in-line, automated modules for *P. pastoris*-based manufacturing, purification, and final formulation processes, resulting in clinical-grade recombinant protein therapies in point-of-care environments [34,35].

Moreover, continuous perfusion fermentation reduced the bioreactor footprint, using a sub-liter bioreactor instead of the conventional 1000+ liter systems used for biologics production, hence allowing the complete platform to be accommodated on a benchtop. The necessity for electricity and pure oxygen to operate the system restricts its application in completely off-grid environments; however, the platform's relatively straightforward technological prerequisites—particularly its peristaltic pump-based liquid handling, which may be compatible with recently developed low-cost, open-source, 3D-printed peristaltic pumps—could facilitate its implementation in resource-constrained contexts, such as active military operations and space missions [36].

4. Biotic-abiotic interaction

In addition to creating unique whole-cell manufacturing platforms, other organizations have shown the capability of integrating synthetic biological systems with abiotic systems to enable use in real-world environments. An example pertinent to improving platform mobility and stability across various climates, while possibly facilitating production capacity in different cell types, is the integration of materials science with engineered biology to create encapsulation-based production platforms. González et al. [37] encased *Bacillus subtilis* spores, recognized for their tolerance to various harsh stressors, inside 3D-printed agarose hydrogels for the on-demand, inducible manufacture of small-molecule antibiotics. The customizable materials were shown to preserve cell viability under various stresses, including ethanol, UV light, radiation, high osmolarity, and low pH. Johnston et al. [38] recently created an on-demand production platform employing functionalized pluronic hydrogels, which possess temperature-responsive and shear-thinning characteristics to facilitate uniform cell distribution and extrudability, respectively. The mechanical durability of these gels offered protection against cryopreservation stress for both bacterial and yeast cells. The platform's adaptability was shown by the continuous and on-demand generation of several value-added compounds from both mono- and cocultures, including L-DOPA, 2,3-butanediol, ethanol, colicin V, and betaxanthins. The capacity to physically segregate cocultures inside distinct hydrogels facilitated the regulation of consortia population dynamics, reducing the need for genetically encoded mutualism.

Yuan et al. [39] recently showcased the portable, reusable, and on-demand synthesis of recombinant proteins up to 150 kDa from encapsulated P. pastoris cells using the Bioproduced Proteins On Demand (Bio-POD) technology. Significantly, these cell-embedded material platforms exhibit resilience to lyophilization, facilitating ambient storage and straightforward on-demand manufacture. This property is particularly crucial for recombinant protein synthesis, which is often characterized by stringent cold-chain requirements. The potential of encapsulation to improve organism stability may be used to production methods using nonconventional hosts, hence broadening the spectrum of cell types suitable for production in extralaboratory environments. A significant barrier persists in integrating these synthetic biology platforms with appropriate downstream purification modules, despite advancements in automated purification module systems [40,41].

As previously emphasized, on-demand and continuous bioproduction necessitates the maintenance of metabolic activity across various environments. The use of microbially induced calcium carbonate (CaCO3) precipitation (MICP) for the generation of functional, regenerable bio-cements may facilitate the efficient, stimuli-responsive manufacture of structural materials in non-laboratory environments. Recent research developed ureolytic *E. coli* to regulate the characteristics of biogenic CaCO3 via genetic manipulation of precipitation rates, therefore showcasing the potential to produce sophisticated functional materials with

genetically modified organisms. Recent research generated living building materials (LBMs) for hostile conditions, using sand-gelatin hydrogel scaffolds infused with cyanobacteria (*Synechococcus*) that can perform microbially induced calcite precipitation (MICP). The resultant materials were capable of regeneration for a minimum of three consecutive cycles via the application of temperature and humidity controls, exhibiting greater microbial viability inside the LBMs after 30 days compared to previously documented data (when sustained at a minimum of 50% relative humidity). Furthermore, the materials may be recycled to function as the abiotic component of new LBMs after they are no longer viable. Nevertheless, the LBMs created to far demonstrate a distinct tradeoff between optimizing cell viability (attained at elevated relative humidity) and enhancing mechanical performance (realized at peak dehydration), necessitating more efforts to bolster the stress tolerance of the encapsulated organisms [43,44].

5. Cell-free manufacturing systems

Cell-free production platforms provide a feasible alternative to conventional cell-based systems for protein and small-molecule synthesis. They are often more conducive to preservation, exhibiting two-month shelf stability via the lyophilization of crude extracts of *E. coli*, along with three months of storage at a higher temperature of 37°C, were facilitated by the incorporation of cryoprotectants and the separate storage of reaction components prior to preservation.

Alongside increased storage capacity, cell-free production systems have been modified for use in distant, resource-limited environments. Pardee et al. [45] created a freeze-dried, paper-based platform for the on-demand production of biomolecules, allowing for the rehydration of freeze-dried cell-free systems and DNA constructs to generate functional products using combinatorial multi-enzyme pathways. Sullivan et al. [46] developed a rapid method for producing μg to mg quantities of therapeutic proteins, including recombinant human erythropoietin (rhEPO) and recombinant human granulocyte-macrophage colony-stimulating factor (rhGM-CSF), by integrating cell-free protein expression with in-line purification capabilities using *Saccharomyces cerevisiae* and *Escherichia coli* cell-free expression systems, respectively. Murphy et al. [47] established the "Therapeutics-On-a-Chip (TOC)" technology by integrating cell-free expression with microfluidics for point-of-care generation of therapeutic proteins. This technology combined continuous-flow manufacturing and batch purification to provide a dosage of the antimicrobial peptide in 6 hours. Adiga et al. [48] enhanced automation by creating a portable Bio-MOD system that employs lyophilized Chinese hamster ovary cell extracts, achieving a complete cGMP-quality production process in less than 9 hours. This platform and the TOC are designed for mobility, since both may be accommodated inside a briefcase for external applications. The platform created by Adiga et al. [48] incorporates self-monitoring process analytical technology (PAT) software for real-time absorbance, pressure, and temperature measurements, alongside additional automated analytical technologies under development that allow the system to operate autonomously with minimal operator intervention, facilitating use by non-experts.

Numerous obstacles persist regarding the implementation of these platforms in the field. Whole-cell platforms provide large-scale synthesis via biomass accumulation and have been shown to be more conducive to incorporating post-transcriptional alterations in protein products than cell-free platforms [48-50]. Consequently, these platforms are optimally designed for applications requiring substantial product volumes and for the synthesis of molecules with intricate glycosylation patterns. Whole-cell platforms may gain from initiatives aimed at improving organism resistance to metabolic and environmental challenges. To enhance environmental stress resilience for shelf stability and long-term performance—essential for continuous production platforms in fluctuating climates—advancements in strain engineering should be integrated with ongoing progress in biotic and abiotic interfacing to create more robust platforms. Moreover, the development of synthetic circuits that are resistant to mutation would improve the genetic stability of organisms, thereby augmenting platform resilience, which is a significant issue for systems required to function in extreme environmental conditions and/or over extended durations during which cells experience elevated mutational stress to maintain viability [51,52].

The advancement of polymers and manufacturing techniques suitable for a broader spectrum of cell types may enhance the variety of host organisms eligible for external production systems, extending beyond those recognized for their greater stress resilience, such as yeast and bacteria. In contrast, the ability of specific organisms, such as *B. subtilis* spores, to endure extreme stressors underscores the necessity for enhanced strain engineering initiatives aimed at utilizing additional stress-resistant hosts to overcome the challenges of deploying living cells in fluctuating climates [53]. Consequently, advancements in materials science and biology may facilitate the practical implementation of whole-cell manufacturing systems outside laboratory settings. In contrast, cell-free platforms are more readily adaptable to achieving shelf stability and may produce results more rapidly by omitting the biomass accumulation phase, but at the expense of the quantity of product generated per reaction. Consequently, these platforms are optimally designed for scenarios requiring rapid procurement of limited product quantities (i.e., 4-6 hours rather than many days). Advancements in the design of reaction systems to achieve higher production titers are essential for facilitating their deployment in production scenarios that need several doses simultaneously. Advancements in cell-free protein synthesis to facilitate the generation of proteins with intricate glycosylation patterns will be necessary to broaden the spectrum of attainable products [54-56].

Advancements in platform automation would enhance the autonomous performance of both whole-cell and cell-free systems. Although numerous systems mentioned have integrated automation features, including real-time monitoring of production and purification processes, additional enhancements to facilitate seamless end-to-end production of consumable products with minimal user intervention (preferably a single 'start' button) would reduce the necessity for professionals to operate the equipment in the field. Moreover, initiatives to reduce system costs would probably be necessary to enable the implementation of on-demand production platforms in resource-limited environments [57]. Strategies to accomplish this encompass emphasizing production from economically viable organisms like bacteria and yeast, integrating continuous production and purification within unified platforms, engineering strains or cell-free reaction mixtures for multiplexed production of various products either concurrently or with production ratios modulated by inducible expression, and reducing costs associated with production and purification equipment potentially through 3D printing using inexpensive raw materials. Although some tactics are used independently on the aforementioned platforms, their integration within each platform will likely be essential for ensuring economic success [58,59].

A viable technique to extend use in harsh environments with restricted or absent power availability may include integrating platforms with microbial fuel cells, using the bio-catalytic capabilities of living cells to transform chemical energy into electrical energy for comprehensive production. Further advancements are necessary to enhance efficiency by increasing electron transfer rates, reducing biofouling and catalyst deactivation, and limiting excessive biofilm growth [60]. Continued progress in this domain may broaden the applicability of on-demand production platforms beyond laboratory settings. Moreover, the need for pure oxygen inputs constrains the application of existing whole-cell systems. The removal of these requirements will likely necessitate either the metabolic reconfiguration of widely utilized bioproduction organisms to reduce oxygen demands (allowing operation from air instead of pure oxygen) or the engineering of bioproduction capabilities in organisms possessing metabolic frameworks suited for survival in oxygen-deprived environments (such as P. aeruginosa). Finally, increased regulatory approvals will be required to deploy these on-demand production platforms in the field [61].

Given that there are already FDA-approved products from continuous whole-cell production platforms, the approval process for these platforms will likely primarily require a demonstration of sufficient product safety and efficacy as those made from approved processes. As there are currently no FDA-approved therapeutics produced via cell-free systems, these platforms will likely face a more arduous path to approval. However, Adiga et al. [48] did incorporate guidance from the FDA Emerging Technology Team on steps needed to enable regulatory acceptance of their products, and Sutro Biopharma is currently undergoing the FDA approval process for therapeutics produced via cell-free manufacturing. Once a cell-free production platform is on the market, approval of cell-free production platforms will hopefully be as (relatively) readily achievable as that of whole-cell systems [51].

6. Future applications for on-demand outside-the-lab biosensing platforms

Biosensing platforms have the potential to transform the safety and efficiency of human performance health such as in remote military missions, space missions, or even in early health event monitoring for at-risk patients. For instance, biocompatible, wearable, or implantable hydrogel-based sensors can be utilized in the field (where there would be limited access to power sources as well as exposure to potentially harsh environmental conditions) to continuously monitor soldier health [62]. Beyond monitoring vital signs, the real-time detection of biomarkers using cellular detectors can proactively monitor potential health and safety issues for individual soldiers on training missions. Likewise, biosensing platforms could also be utilized for biometric applications and identity verification, serving as a barrier to security threats in areas where limited security infrastructure exists. Continuous health sensors and diagnostics tests can seamlessly integrate with the WHO's initiatives to promote widespread adoption of mHealth (mobile health) to enable individuals in remote regions to interact with healthcare professionals to obtain timely care [63,64]. Biosensing devices, either wearable or implantable, capable of transmitting data via Bluetooth, could notify healthcare professionals if an individual consistently exhibits symptoms necessitating medical attention, thereby eliminating the need for in-person visits, which may be impractical for those in remote areas. Fully integrated, field-deployable wearable platforms have not been widely demonstrated due to ongoing concerns related to issues such as long-term sensor stability concerns and the need for demonstration of sensing capabilities beyond a few simple biomarkers [65]. Ideally, the integration of encapsulation techniques discussed in this section together with more complex genetic circuits and improvements in sensor stability in metabolically active states could enable deployment of these platforms in outside-the-lab settings.

7. Conclusions

Synthetic biology is expanding to applications outside the lab. On-demand production of compounds, therapeutics, and materials can obviate the need to stockpile medicines, fuel, or general resources on remote military and space missions. Continuous biosensing of individual health biomarkers and hazards has numerous applications for enhanced healthcare and security in remote regions around and outside the globe. Closed-loop delivery of living therapeutics and engineered probiotics can combat medication noncompliance and antimicrobial resistance, as well as provide sustainable alternatives for chemical fertilizers and pesticides in agricultural regions on Earth and ultimately on Mars and beyond. Reaching these applications will require multidisciplinary work including strategies discussed in detail in the 'ongoing challenges' sections described above. Across all of these are needs to stabilize strains for robust performance, enable simple-to-use responsive/autonomous biology, interface biotic-abiotic systems seamlessly, and embrace platform simplicity and ease of use.

While the recent advancements were organized into application spaces as a way to contextualize their uses, it should be noted that many of the platforms in this Perspective fit multiple categories and thus have transferrable elements that are more broadly applicable. While numerous systems were initially developed for specific applications, progress in stabilizing encapsulated cells or enhancing multifunctional cell-free assays, for instance, could result in enhancements relevant to any technology intended for use in external laboratory environments. Through continued interdisciplinary innovation, it is possible to develop robust, cost-effective, safe, efficacious platforms that can translate innovative synthetic biology-based technologies developed in the lab into real-world applications in outside-the-lab scenarios. These scenarios can greatly advance many of the grand challenges we face today.

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التطورات في علم البيولوجيا التركيبية لتطوير أدوات تشخيص مختبرية مبتكرة: مراجعة شاملة

الملخص

الخلفية: برز علم الأحياء التركيبية كمجال تحويلي يتمتع بالقدرة على معالجة التحديات العالمية في مجال الصحة والاستدامة وإمكانية الوصول إلى الموارد. يستكشف هذا الاستعراض التطورات في علم الأحياء التركيبية بهدف تطوير أدوات تشخيصية جديدة للمختبرات. نقوم بتحليل المنهجيات المستخدمة في الأنظمة المعتمدة على الخلايا والأنظمة الخالية من الخلايا، مع التأكيد على قابليتها للتطبيق في بيئات متنوعة، بما في ذلك الإعدادات المحدودة الموارد والتي تعمل خارج الشبكة.

الطرق :تُجمع هذه المراجعة النتائج المستخلصة من دراسات حديثة تُظهر التنفيذ الناجح لتقنيات علم البيولوجيا التركيبية في السيناريوهات الواقعية، مثل الإنتاج الحيوي، واستشعار البيولوجيا، وتوصيل العلاجات.

النتائج :تشير النتائج إلى أنه بينما تقدم الأنظمة المعتمدة على الخلايا مزايا في الإنتاج الكمي والتعقيد، فإن الأنظمة الخالية من الخلايا توفر استقرارًا ومرونة أكبر لتشخيصات سريعة. ومع ذلك، تواجه كلا الطريقتين تحديات كبيرة، بما في ذلك الاستقرار الجيني، ومتطلبات الموارد، وتعقيد العمليات. تبرز المراجعة ضرورة اتخاذ نهج متعدد التخصصات لتجاوز هذه العقبات وتحسين متانة وقابلية استخدام تطبيقات علم البيولوجيا التركيبية.

الخاتمة :في النهاية، نستنتج أن الابتكار المستمر في علم البيولوجيا التركيبية يمكن أن يؤدي إلى إنشاء أدوات تشخيصية فعّالة تستجيب ليس فقط للاحتياجات الطبية الفورية، ولكن أيضًا تكون مستدامة للاستخدامات المستقبلية في السياقات النائية ومحدودة الموارد.

الكلمات المفتاحية :علم البيولوجيا التركيبية، أدوات التشخيص، الأنظمة المعتمدة على الخلايا، الأنظمة الخالية من الخلايا، الإنتاج الحيوي.