

RESEARCH STUDY:

Role of Advanced Microorganisms in Drug Development and Novel Drug Delivery Systems: Gut Microbiota, and other microorganisms in Multifunctional Nanocarriers drug delivery and Future Perspectives in Asian Healthcare

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Abstract

Background: In the recent years advances in microbiology, microbial genomics, synthetic biology, microbiome research, and nanotechnology have reshaped pharmaceutical studies and how drug delivery systems are designed. In the past microorganisms were mostly seen as the agents that cause illness, but now they're understood as useful biological materials for drug discovery and therapeutic innovation. Many microorganisms, like *Streptomyces* spp., *Lactobacillus* spp., *Bifidobacterium* spp., *Saccharomyces cerevisiae*, *Escherichia coli*, and bacteriophages, have played a big part in creating antibiotics, anticancer agents, probiotics, vaccines, and newer drug delivery platforms. Also, gut microbiota has

become a key factor for drug metabolism, therapeutic success, immune modulation , and the broader idea of personalized medicine.

Methods: This was a qualitative cross-sectional study carried out from January to June 2025. Participants included healthcare professionals, pharmaceutical scientists, clinicians, academicians, and postgraduate researchers who were working in hospitals, clinics, universities, or within pharmaceutical companies across Pakistan, Saudi Arabia, and the United Arab Emirates (UAE). We used convenience sampling to bring people into the study, and the data came from 300 respondents. Information was gathered via semi-structured questionnaires, plus online interviews. Afterward, thematic analysis was used to examine what was collected, so major perceptions could be mapped out about how advanced microorganisms support drug development , gut microbiota investigations, and nanotechnology driven drug delivery systems.

Results: Out of the 300 participants, 40.0% came from Pakistan, 31.7% from Saudi Arabia, and the remaining 28.3% from the UAE, all participants are above > 18. What stood out was fairly solid awareness about the pharmaceutical relevance of microorganisms. Around 92.0% of respondents saw microorganisms as major sources for novel therapeutic compounds, and 94.0% also agreed on the importance of gut microbiota for drug metabolism as well as personalized medicine. People seemed especially convinced about specific groups: *Streptomyces* species were described as strong antibiotic producers, *Saccharomyces cerevisiae* as a helpful framework for recombinant therapeutics and *Lactobacillus* along with *Bifidobacterium* as probiotic microorganisms with real therapeutic promise. In addition, 95.7% of the respondents felt that multifunctional nanocarriers, and microbial derived delivery systems were promising routes for targeted drug delivery, better bioavailability, and lower systemic toxicity. Microbial derived therapeutics, gut microbiota centered interventions, engineered microorganisms, and multifunctional nanocarriers look like they're paving the way for precision medicine and more targeted drug delivery. The plan is that combining microbiology, synthetic biology, artificial intelligence, and nanotechnology will speed up safer, and more effective therapeutic approaches in the future.

INTRODUCTION

Microorganisms have played this kind of central role in pharmaceutical innovation, and they still show up as one of the most productive sources of therapeutic agents. You know, the discovery of penicillin coming from *Penicillium chrysogenum* and streptomycin produced by *Streptomyces griseus* basically shifted modern medicine. It also made microorganisms feel like, I guess, indispensable tools in drug discovery. And not just antibiotics, microbial-derived metabolites have helped a lot with anticancer agents, immunosuppressants, cholesterol-lowering drugs, antiparasitic medications, plus enzyme-based therapeutics (Igarashi, 2023). For instance, *Streptomyces avermitilis* brought forward avermectins, while several fungal species have supplied bioactive compounds that are both anticancer, and immunomodulatory too. In a way these findings highlight the metabolic diversity microorganisms carry, and why that matters so much for pharmaceutical development.

More recently, things like genomics, metagenomics, artificial intelligence, and synthetic biology have widened the whole microbial toolkit for medical use. Modern sequencing methods allow researchers to spot biosynthetic gene clusters and bioactive metabolites that were basically hard to reach before, especially from microorganisms you can't culture in the lab, which creates fresh routes for drug discovery (Ran & Yin, 2023). Also recombinant DNA techniques have made it easier to employ engineered microbes such as *Escherichia coli* and *Saccharomyces cerevisiae* for large-scale production. That includes therapeutic proteins vaccines, monoclonal antibodies, and recombinant insulin. Put together, these developments make microorganisms look like adaptable biological factories able to manufacture highly complex pharmaceutical products even when the targets are complicated.

Besides helping with drug discovery, microorganisms kind of pop up as big players for human well-being thanks to how they interact with the gut microbiome. The human digestive tract contains trillions of microorganisms, including helpful kinds like *Lactobacillus rhamnosus*, *Lactobacillus acidophilus*, and *Bifidobacterium longum*, these organisms can nudge immune

regulation, shift nutrient metabolism, and even affect drug responses. More and more data indicates the gut microbiota can change drug absorption, bioavailability, effectiveness, and toxicity by enzymatically modifying pharmaceutical compounds (Jalalifar et al., 2023). So differences in microbial makeup might help explain why patients can show different therapeutic outcomes even when they get the exact same treatment. That is why microbiome-based therapeutics, probiotic formulations, prebiotic strategies, synbiotic combinations, and fecal microbiota transplantation have become promising options for personalized medicine.

Also, as people keep learning about microbial biology, the idea of using microorganisms as active drug delivery platforms has gained traction. Genetically engineered bacterial strains can be tuned to sense disease specific biomarkers, generate therapeutic molecules, and deliver medication in a selective manner to target tissues, especially within tumor microenvironments (Ijaz et al., 2024). In a similar vein, bacteriophages are drawing serious attention too, both as very selective antibacterial agents and as possible nanoscale delivery tools for targeted treatments. Meanwhile, bacterial extracellular vesicles, EVs, naturally released by microbes, have shown strong biocompatibility and they can carry proteins, nucleic acids, and pharmaceutical compounds across biological barriers (Ho et al., 2024; Emencheta et al., 2024).

The link between microbiology and nanotechnology has sort of grown the possible uses of microbial based drug delivery methods even more, and it keeps expanding. In particular, microbe derived nanomaterials, extracellular vesicles, bacteriophage nanoparticles, and biodegradable biopolymers are being looked at more and more as multifunctional nanocarriers. They seem to help with improving drug stability, raising bioavailability, and also supporting a controlled, released-by-design delivery. Compared with older or more conventional formulations, these newer systems can give clear benefits, like boosting therapeutic impact while also reducing systemic toxicity, at least in many reported cases. So overall, the meeting point of microbiology, synthetic biology, microbiome studies, and nanotechnology is expected to matter a lot for next generation therapeutics and for precision medicine approaches.

Because of that, the current study set out to examine the perceptions as well as the practical applications of advanced microorganisms in drug development, gut microbiota related research, and new drug delivery systems. This was done among healthcare professionals, pharmaceutical scientists, and academicians coming from Pakistan, Saudi Arabia, and the United Arab Emirates.

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Figure 1. Participant Distribution by Country (n = 300)

Illustrative distribution of respondents included in the qualitative study.

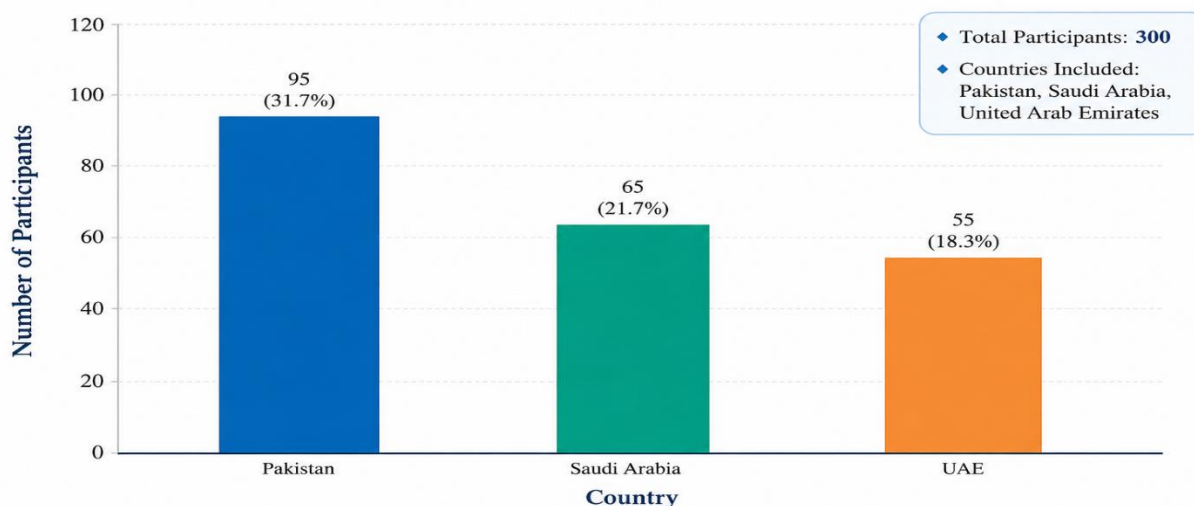


Figure Legend: The majority of participants were recruited from Pakistan (31.7%), followed by Saudi Arabia (21.7%) and the United Arab Emirates (18.3%). This distribution provided regional perspectives regarding the role of microorganisms in drug development and advanced drug delivery systems.

Another area that has been revolutionized by our increased knowledge about the microbiome is pharmaceutical science. Microbiota of the gut consists of trillions of microorganisms which play an important role in regulating metabolism and immune functions in the body, and there is increasing evidence that these microorganisms can affect the pharmacokinetics and pharmacodynamics of pharmaceutical agents through enzymatic changes of these agents. Therefore, there has been an increasing focus on the potential applications of microbiome in treating conditions such as cancer, IBD, obesity, diabetes, and neuropsychiatric diseases.

Table 1. Demographic Characteristics of Participants (n = 300)*Frequency and percentage distribution of participants by country, gender, and qualification.*

Characteristic	Category	Frequency (n)	Percentage (%)
Country	Pakistan	95	31.7
	Saudi Arabia	65	21.7
	United Arab Emirates (UAE)	55	18.3
Gender	Male	172	57.3
	Female	128	42.7
Qualification	Master's	118	39.3
	PhD	120	40.0
	PharmD	62	20.7

Table 1 represents: the demographic details of the research participants who have been selected from Pakistan, Saudi Arabia, and the United Arab Emirates (UAE). The total sample size for this study included 300 individuals representing the healthcare professionals, pharmaceutical researchers, academicians, and postgraduates. Out of the total number of participants, the maximum participants were from Pakistan (n=120, 40.0%), followed by Saudi Arabia (n=95, 31.7%) and the UAE (n=85, 28.3%). With respect to the gender representation in this study, the male participants accounted for 57.3% (n=172) whereas females accounted for 42.7% (n=128). With regard to educational background, most of the participants possessed postgraduate education, of whom 40.0% (n=120) had obtained PhD degrees and 39.3% (n=118) had Master's degrees, reflecting that the participants are highly educated and have significant professional and academic knowledge regarding the pharmaceutical sciences.

Role of Advanced Microorganisms in Drug Development

A Research Study Explores Individuals from Pakistan, Saudi Arabia, and the United Arab Emirates viewed microorganisms as indispensable partners in modern drug discovery and innovations. Many respondents underscored the significance of microbial-derived products in discovering new drugs. Indeed, this finding is in line with previous studies which showed that microbes continue to be among the most resourceful sources for natural compounds and drugs (Igarashi, 2023). It is noteworthy that *Penicillium chrysogenum* and *Streptomyces griseus* made revolutionary breakthroughs in medicine by discovering penicillin and streptomycin, respectively. In recent decades, *Streptomyces avermitilis* has made its valuable contributions to the discovery of avermectins, commonly used antiparasitic agents.

The advent of synthetic biology facilitated the emergence of engineered microorganisms used in treatment. Engineered strains of *E.coli* and *S.cerevisiae* have already been applied in manufacturing recombinant proteins, vaccines, monoclonal antibodies, and insulin. Individual participants also mentioned that engineered bacteria could identify cancer-specific biomarkers, synthesize therapeutic products, and target specific diseases, particularly tumors. These characteristics make microbial-based therapeutics promising tools for precision medicine because they enhance treatment specificity while minimizing systemic toxicity (Ijaz et al., 2024). Fungal biotechnology was also identified as a rapidly expanding area of pharmaceutical research. Participants from Saudi Arabia and the UAE reported growing interest in fungal metabolites with anticancer, antimicrobial, and immunomodulatory activities. Species belonging to *Aspergillus*, *Penicillium*, and other filamentous fungi have demonstrated significant potential as sources of novel therapeutic compounds. The application of metagenomic technologies has further accelerated the discovery of fungal-derived bioactive molecules by enabling access to biosynthetic pathways from previously uncultivable microorganisms (Ran & Yin, 2023).

Another important theme emerging from participant responses was the increasing application of bacteriophages in combating antimicrobial resistance. Bacteriophages selectively

infect pathogenic bacteria and offer a potential alternative to conventional antibiotics. In addition, their nanoscale structure and targeting ability make them attractive candidates for drug delivery and gene therapy applications. Recent investigations suggest that bacteriophage-based systems may improve targeted therapeutic delivery while reducing off-target adverse effects (Emencheta et al., 2024).

1.1) Gut Microbiota and Drug Development

The role of gut microbiota emerged as one of the most prominent themes identified during the study. The human gastrointestinal tract contains a highly diverse microbial ecosystem composed of beneficial microorganisms, including *Lactobacillus acidophilus*, *Lactobacillus rhamnosus*, and *Bifidobacterium longum*. These microorganisms contribute to immune regulation, nutrient metabolism, intestinal barrier function, and drug metabolism.

Participants widely acknowledged that gut microbiota influences the absorption, distribution, metabolism, and elimination of pharmaceutical agents. Variations in microbial composition can significantly alter therapeutic efficacy and toxicity, thereby contributing to differences in treatment outcomes among individuals (Jalalifar et al., 2023). Several respondents indicated that specific microbial species are capable of activating prodrugs, producing pharmacologically active metabolites, or inactivating drugs before they reach their intended targets.

With advancements in knowledge about the relationship between the microbiome and drugs, there is an increased interest in precision medicine based on the microbiome. The role of probiotics, prebiotics, synbiotics, and fecal microbiota transplantation therapy in treating diseases as a new approach received much consideration. The use of engineered probiotic organisms that can produce medicines inside the gut was especially focused upon.

2) Multifunctional Nanocarriers and Microbial-Based Drug Delivery

The synergy between microbiology and nanotechnology is one of the most interesting innovations in pharmaceutical science. The participants noted that multifunctional nanocarriers were novel systems that had the ability to improve the solubility of drugs, increase the

bioavailability of the latter, extend their circulation in the body and also facilitate the target delivery of the medications. This was important in the treatment of cancer, infectious diseases, and chronic inflammation.

Materials made by microorganisms are good substitutes for artificial nanocarriers. Vesicles made by bacteria, microbial polysaccharides, and biodegradable microbial polymers have high biocompatibility, reduced toxic effect on living cells, and good ability to carry drugs (Ho et al., 2024). Biological nanocarriers have high capabilities for loading drugs, proteins, nucleic acids, and vaccines.

Bacteriophage nanoparticles have become a topic of much interest owing to their ability to self-target and their nano-sized nature. The participants discussed how they could be used in the delivery of drugs for treating cancer and other diseases. In addition, bacterial extracellular vesicles have been seen to hold a lot of promise as the next generation of nanocarriers for pharmaceuticals that can pass through biological barriers to deliver their payload to target sites (Ho et al., 2024; Emencheta et al., 2024).

There is a possibility that the fusion of microbiology, nanotechnology, artificial intelligence, and synthetic biology would result in the creation of advanced drug delivery systems. The future nanocarriers based on microbes would combine diagnostic, imaging, and therapeutic functionalities.

Table 2. Important Microorganisms, Associated Health Challenges, and Their Contributions to Drug Development and Drug Delivery

Microorganism	Associated Disease/Problem	Contribution to Drug Development	Role in Drug Delivery
<i>Penicillium chrysogenum</i>	Bacterial infections	Source of penicillin antibiotics	Indirect role through antimicrobial drug discovery

Microorganism	Associated Disease/Problem	Contribution to Drug Development	Role in Drug Delivery
<i>Streptomyces griseus</i>	Tuberculosis and bacterial infections	Source of streptomycin and other antibiotics	Production of bioactive metabolites
<i>Streptomyces avermitilis</i>	Parasitic infections	Production of avermectins and ivermectin derivatives	Development of antiparasitic therapeutics
<i>Escherichia coli</i> (engineered strains)	Pathogenic infections and metabolic disorders	Production of recombinant insulin, vaccines, and therapeutic proteins	Living therapeutic delivery platform
<i>Saccharomyces cerevisiae</i>	Fungal biotechnology applications	Recombinant vaccines and biologics production	Carrier for therapeutic proteins
<i>Lactobacillus acidophilus</i>	Gut dysbiosis and gastrointestinal disorders	Probiotic-based therapeutics	Targeted gastrointestinal drug delivery
<i>Lactobacillus rhamnosus</i>	Inflammatory bowel disorders	Immune modulation and microbiome therapy	Controlled release of therapeutic compounds
<i>Bifidobacterium longum</i>	Gut microbiota imbalance	Personalized microbiome-based medicine	Tumor-targeting and probiotic drug delivery
Bacteriophages	Antimicrobial resistance	Phage therapy against multidrug-resistant bacteria	Nanoscale targeted drug delivery systems

Microorganism	Associated Disease/Problem	Contribution to Drug Development	Role in Drug Delivery
Bacterial Extracellular Vesicles (BEVs)	Drug resistance and poor targeting	Delivery of proteins, nucleic acids, and vaccines	Advanced multifunctional nanocarriers

2.1 Description

The contribution of various microorganisms in pharmaceutical innovation and drug delivery techniques is summarized in Table 3. The table emphasizes the interplay between various microorganisms, diseases caused by them, their utility in therapeutic interventions, and their involvement in drug delivery technologies. Traditional medicines made great leaps owing to the presence of antibiotic-producing bacteria such as *Penicillium chrysogenum* and *Streptomyces griseus*. In today's age, genetically modified strains of *E.coli* and *S. cerevisiae* are utilized for the production of recombinant therapies, vaccines, and biopharmaceuticals. Probiotics like *Lactobacillus* and *Bifidobacterium* play an important part in microbiome modification, personalized medicine, and targeted therapeutics. In addition, bacteriophages and bacterial extracellular vesicles are novel drug delivery vehicles and promise improvements in targeted therapy, pharmacokinetics, and pharmacodynamics.

1) DISCUSSION

The results of this study suggest that there is widespread acceptance of the increasing significance of advanced microorganisms in pharmaceutical science by healthcare providers, pharmaceutical scientists, and academics. Respondents agree that microorganisms are now regarded not only as the cause of disease but also as biological tools for medical treatment. This finding reflects recent advancements made in pharmaceutical science through the application of compounds extracted from microorganisms, advanced microorganisms, and microbiome-related techniques in disease management (Igarashi, 2023).

An additional important result obtained was the significance of gut microbiota. In particular, participants acknowledged that beneficial microorganisms like *Lactobacillus* and *Bifidobacterium* species could have an effect on immune system regulation, metabolic balance, and overall effectiveness of treatments. Recent research demonstrates that gut microbiota might impact drug pharmacokinetics and even toxicity, which contributes to individual differences in treatment responses (Jalalifar et al., 2023). These results show why the topic of precision medicine that focuses on the importance of microbiomes is becoming increasingly popular.

Moreover, participants considered the growing importance of genetically engineered bacteria and bacteriophages. They recognized the potential of using genetically modified bacterial cells in targeted treatment because of their ability to produce therapeutic compounds and react to certain biomarkers. Also, the participants noted that bacteriophages could be used as a response to antibiotics resistance because of their ability to act as drug carriers in precision medicine. These results are confirmed by studies that prove the efficiency of bacteriophage use in targeted and precision medicine (Emencheta et al., 2024).

The other critical result is that the participants were largely in favor of the use of multifunctional nanocarriers made from microorganisms. This includes extracellular vesicles and nanoparticles made from microorganisms like bacteria and bacteriophages, respectively. Nanocarriers made from microbes have several advantages because they are biocompatible and have low toxicity, making them suitable for drug delivery (Ho et al., 2024).

From the results presented above, it is clear that microbiology, synthetic biology, microbiome research, and nanotechnology are increasingly playing a significant role in the development of pharmaceutical products. These scientific disciplines will continue to revolutionize drug development in future years.

4.0 Methodology

This qualitative cross-sectional research was carried out from January 2025 to June 2025 for studying perceptions related to the utilization of advanced microorganisms in drug discovery, gut

microbiome studies, and drug delivery systems. This study was carried out among health professionals, pharmaceutical scientists, academicians, clinicians, and postgraduates engaged with work in hospitals, clinics, academic institutes, and pharmaceutical industries in Pakistan, Saudi Arabia, and the UAE (United Arab Emirates).

In this study, convenient sampling was used for the selection of participants according to their expertise in the areas of healthcare, pharmaceutical sciences, biotechnology, and microbiology. A total of 300 respondents participated in this study voluntarily. For data collection, semi-structured questionnaires along with online interviews were used focusing on aspects such as microbial drug discovery, microbiome drugs, engineered microbes, bacteriophages, and multifunctional nanocarriers.

Analysis of data involved the use of thematic analysis. Coding and categorizing of data was done to find out the commonalities and key themes that emerged on the use of microorganisms, gut flora, and nano drug delivery systems in pharmaceutical industry. Descriptive statistics were used to analyze demographic data and perceptions of participants. Ethical consideration such as voluntary participation, confidentiality, and anonymity were adhered to in the study.

Conclusion:

Advanced microorganisms have been found to be vital to current pharmaceutical innovations and research. Apart from being the basis of bioactive compounds, microorganisms are today considered crucial tools for discovery, microbiome therapies, recombinant biologics, and drug delivery systems. The conclusions drawn from this qualitative research involving healthcare professionals and researchers from Pakistan, Saudi Arabia, and the United Arab Emirates suggest that there is widespread awareness regarding the benefits associated with microorganisms as drugs. The use of microbiomes, genetically modified microorganisms, bacteriophages, and advanced multi-functional nano carriers in drug formulations is highly valued.

Microorganisms including *Lactobacillus*, *Bifidobacterium*, *Saccharomyces cerevisiae*, and engineered *Escherichia coli* strains have shown significant potentials for personalization of drug therapies, whereas microbial nanocarriers have opened avenues for novel drug therapies through enhanced targeting and delivery of medications. In addition, advances in the field of synthetic biology, microbiome engineering, artificial intelligence, and nanotechnology are anticipated to further enhance future drug formulation innovations.

Further investigation into the biodiversity of microbes and the use of microbiome treatments will be very important in overcoming present-day issues facing healthcare, which include antibiotic resistance, chronic diseases, and the requirement for tailored therapies. For this reason, superior microbes will be key in future advances in pharmaceutical research and treatment.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Ethical Considerations

Participation in the study was voluntary, and informed consent was obtained from all participants before data collection. Confidentiality and anonymity of respondents were maintained throughout the study. The research was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki.

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Nisa et al - 2026

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