WORLD JOURNAL OF PHARMACEUTICAL RESEARCH
Coden USA: WJPRAP Impact Factor 8.453
Volume 15, Issue 3, 863-903. Research Article ISSN 2277–7105

IMPLEMENTATION OF BIOTECHNOLOGY IN AYUSH - BRIDGING TRADITION AND MODERNITY

***[1]Madhuri Patel, [2]Omprakash Patel, [3]Lavali Vishwakarma**

*[1]Assistant Prof., SSPU, Bhilai, C.G. – 490020, India.

[2]Assistant Prof., NEIAH, Shillong, Meghalaya – 793018, India.

[3]PGT, RVHMC, Udaipur, Rajsthan -313022, India.

Article Received on 30 Dec. 2025,
Article Revised on 19 Jan. 2026,
Article Published on 01 Feb. 2026,

https://doi.org/10.5281/zenodo.18430497

***Corresponding Author**

Madhuri Patel

Assistant Prof., SSPU, Bhilai, C.G. – 490020, India.

How to cite this Article: *[1]Madhuri Patel, [2]Omprakash Patel, [3]Lavali Vishwakarma (2026). Implementation Of Biotechnology In Ayush - Bridging Tradition And Modernity. "World Journal of Pharmaceutical Research, 15(3), 763–903.

ABSTRACT

Various methods of treatment, called ‘medical systems’ coexist in the present world with different amplitude of popularity because every healthcare system possesses inherent limits that may also be present in other medical systems or complement it. The collaboration between other disciplines contributes to the progress of each medical system, enhancing its ability to effectively serve humanity. Furthermore, biotechnology has established a strong basis and evidence for advancing research and development in the medical domain, encompassing the enhancement of both the medical sector and the pharmaceuticals employed. AYUSH is not likely to flourish in isolation. The incorporation of biotechnology into the AYUSH (Ayurveda, Yoga and Naturopathy, Unani, Siddha, and Homeopathy) system of medicine has significant potential to improve the effectiveness, safety, and standardization of treatments. This review explores the potential for transdisciplinary research between AYUSH and biotechnology. It also provides a critical assessment of the current state, challenges, and anticipation of biotechnological interventions in AYUSH. The review highlights significant advancements, limitations, and opportunities for collaboration between traditional knowledge and modern biotechnology.

KEYWORDS: AYUSH, Biotechnology, Traditional Medicine, Personalized Medicine, Drug Discovery, Standardization, Transdisciplinary Research.

Highlights

- This review covers biotechnological techniques till now utilized and can be used in the future for AYUSH-recommended drugs.
- In this review, we discussed transdisciplinary research between AYUSH and biotechnological fields like microbiology, plant biotechnology, nanotechnology, bioinformatics, etc.
- It highlights the positive impact of collaboration on the AYUSH system, with biotechnology.
- Opportunities for collaboration between traditional knowledge and modern biotechnology.
- Limitations and benefits from traditional medicine system that uses biotechnological techniques.

INTRODUCTION

The AYUSH system of medicine, rooted in ancient Indian wisdom, encompasses a diverse array of traditional healing practices aimed at promoting holistic health and wellness. Approximately about 80 % of people in the world prefer it as primary health care because of no side effects on the body (Gopal et al., 2023). In 1995, the division was established under the name Department of ISM (Rudra et al., 2017) and subsequently evolved into a separate Ministry of AYUSH in 2014. AYUSH systems and allopathic systems are ontologically and epistemologically different but the source for medicine preparation is the same i.e. plants, animals, minerals, microbes, and chemicals (Srivastava et al., 2020). The pharmacological advancement is different, and likewise, their explanations for pharmacological actions and interactions are different. Although Ayurvedic medicine predates contemporary medicine, its progress within the philosophical framework has been constrained and fixed in time. Moreover, biotechnology offers a common ground for convergence of AYUSH and Allopathic (modern) medicine, without shaking their philosophical foundations. The broad spectrum of applications of biotechnology on Ayurvedic plant medicines, including plant tissue culture for developing better and disease-resistant varieties as well as increasing production (Vanisree et al., 2004; Zhou and Wu; 2006), diagnostics for medicinal plant pathogens (Mitchum et al., 2007), plant genetic engineering for secondary metabolite production from medicinal plants (Tripathi and Tripathi, 2003) detection of markers of established active principles (Ganie et al., 2015), pharmacognosy for novel drugs (Phillipson, 2007), exploitation of microbial processes and soil microorganisms (Singh, 2010), storage

and bioprocessing of crude medicinal materials, and so on. It also protects the germplasm of endangered medicinal plant species (Nanaware et al., 2024). Transgenic technologies and chemical synthesis can also be used on an industrial scale to produce well-defined active principles or those derived from non-cultivable plants and endangered animal-derived therapeutic agents which are used in the AYUSH system of medicine (Li, 2024). However, regardless of its rich history and extensive popularity, the AYUSH sector confronts several obstacles, including poor scientific validation, standardization issues, and the need for evidence-based practices. So, interdisciplinary research in Ayurveda with biotechnology cutting-edge biotechnological methods and advanced equipment is available to identify the components present in crude extract and determine its biological activity, and lastly, the clarification of structures, followed by the bioavailability of the substance either alone or in combination. Biotechnology enables us to employ bacteria, animals, and plants as cells, tissues, organs, or complete organisms by cultivating them *in-vitro* and genetically altering them to create needed substances (Santos-Beneit, 2024; Rao and Ravishankar, 2002). Additional preclinical investigations, such as toxicity, stability, and solubility studies, are carried out on the molecule if it has strong pharmacological effects and is deemed attractive (Srivastava et al., 2020). The incorporation of biotechnology offers a promising approach by employing advanced techniques to address these issues and unlocking the full potential of AYUSH therapies (Lele and Patwardhan, 2020; Chauhan et al., 2023).

The efficacy of the manufacturing process in deactivating or eliminating adventitious factors is essential for maintaining the biological safety of the first, safe formulation of the homeopathic medicinal product. Stringent precautions must be implemented to minimize the risk of infection agents in homeopathic remedies, ensuring compliance with the requirements outlined in the European Pharmacopoeia monograph on homeopathic remedies. Furthermore, herbal medicine is a plant-based crude extract that contains various heterogeneous chemicals and has been utilized as a therapeutic agent throughout history (Mosihuzzaman, 2012; Srivastava et al., 2020; Kamboj, 2000). Furthermore, the phytochemical extracts exhibit significant diversity owing to the presence of many bioactive constituents (Ramawat and Arora, 2021). A desirable biological reaction may be due to a mixture of multiple bioactive chemicals, rather than a single one (Orhan et al., 2008; Srivastava et al., 2020).

Classical and modern ways to prepare Ayurvedic medicine

It is one of the earliest medical systems and contains various medicinal principles. Although there are distinctions in the nature of existence and knowledge between AYUSH traditions and modern allopathic medicine. However, the main sources of drugs and supplements, such as plants, animals, microbiota, minerals, and chemicals, are mostly the same (Dasgupta, 2023). There are various ways to make drugs in ancient times such as soaking, fermenting, boiling, drying, chilling, grinding, etc., and preparing drugs in the form of powder, decoction, oil, and fermented herb extract. Furthermore, in old times there were no ideas about how drugs work and what proportion they combine with other molecules. Ayurvedic medicine is indeed older than modern medicine, but its spiritual development has been limited and stuck in time. Ayurveda is a science of life that prioritizes a holistic approach to health and customized restoration (Nithin et al., 2022). It didn't change along with modern science, and until lately last decades, it didn't allow the use of modern technology for developing drugs, testing them for safety and effectiveness, and writing about how drugs work on patients. AYUSH possesses the capability to treat a variety of diseases, for instance, cancer, diabetes, arthritis, and asthma, that are currently untreatable by modern medicine (Javed et al. 2024; Mishra et al., 2024; Bhide & Nitave, 2024). The scientific community does not readily embrace a comprehensive comprehension of the fundamental Ayurvedic concepts due to a scarcity of supporting data. In the present day, the Ayurvedic system of medicine needs validation of its fundamental concepts and medications through the implementation of enhanced research methods (Nawab and Sherwani, 2024). Modern pharmaceuticals include standardized manufacturing, quality control, and improved analytical procedures. It also has improved bioavailability, stability, and reproducibility (Giratkar and Kubde, 2024). Ayurveda–modern medicine interface has given Ayurvedic medicines a platform to treat osteoarthritis and rheumatoid arthritis (Chopra et al., 2010). This is especially significant considering the fact that the Western medicinal system has virtually reached its pinnacle as a result of validated research and advanced procedures (Nawab & Sherwani, 2024). Consequently, there is an urgent need to enhance the current research methodology in order to advance Ayurveda. It is imperative to integrate Ayurvedic preparations with contemporary processing principles to enhance the output of the medications and meet the increasing demand. It is also essential to understand the fundamental Ayurvedic concepts that underlie formulation and processing to enhance the dosage forms. Although the Ayurvedic sector has incorporated technology from the pharmaceutical, chemical, and food industries, there has been no systematic research to compare ancient and contemporary processing methods (Rani

et al., 2023). Biotechnology provides a shared platform for the integration of AYUSH and Allopathic medicine, without compromising their underlying philosophical principles.

The necessity for advancement and innovation in AYUSH

Despite the considerable growth of the Ayush system in recent years, there remains a need for further enhancement. Nevertheless, to promote development in the Ayush sector, it is essential to use creative approaches that cater to the public's needs and bridge the gap between advanced biotechnological techniques and Ayush systems. In addition, an alternative approach to assessing Ayush systems could involve evaluating the efficacy of its treatment principles for a specific clinical condition, rather than focusing on individual drugs. Furthermore, it is necessary to conduct deeper research on the principles of Ayush employing state-of-the-art technologies to enhance our comprehension. Advanced tools are necessary to gain a deeper understanding of subjects such as biotechnological tools. Novel methodologies for assessing the quality of Ayush medications should be created. In order to cultivate a research environment that produces significant results, it is necessary to enhance and modernize Ayush research institutions with state-of-the-art technology. Ayush scholars require enhanced access to contemporary diagnostic methods such as MRI and tomography scans. It is necessary to establish skill laboratories to enhance the quality of training. Robust research investigations are necessary to validate or revalidate the Ayush system in the current situation. Conducting rigorous investigations on the safety, quality, and efficacy of pharmaceuticals and processes is crucial. The Ayush pharma sector and the export of Ayush medicines have a vast innovation potential. There is an opportunity to develop novel study designs for evaluating Ayush medications, as these systems prioritize personalized treatment. Moreover, it will have a positive impact on the economy. When considering innovations in the Ayush industry, it is crucial to use a distinct strategy. Aside from seeking novel concepts and innovations, there are also substantial opportunities and significant chances for success by exploring past experiences and internal resources (Gopal et al., 2023).

Biotechnological Interventions in AYUSH for research and development

Technologies that improve bioavailability and decrease particle size, as well as fractional design and targeted medication administration by dosage, are unique to Ayurvedic science. Bioactive chemicals, which may cover more chemical ground and offer information on safety and efficacy, also improve traditional therapy. Chromatography, infrared studies, enzymatic immunoassays, DNA and genomic fingerprinting, and other recent scientific and

technological developments can shed insight into a potential future solution to the problem of discovering natural products (Yadav and Gupta, 2022). Biotechnological techniques can be employed to thoroughly investigate the compositions of medications and their molecular impacts. Biotechnological techniques have been used such as Western blot, ELISA, MTT assay, enzyme assays, etc for the anti-inflammatory impact of Kaba Sura Kudineer (Jose et al., 2023), an AYUSH-authorized medicine for COVID-19, was studied in RAW-264.7 macrophage cells (Gupta et al., 2023). Their study focused on its ability to counteract the inflammatory response generated by lipopolysaccharide. It has the potential to be a therapeutic medication for reducing excessive inflammation in several disorders connected with inflammation, such as COVID-19 (Jose et al., 2022). For many medicinal plant extract purification HPLC (High Pressure Liquid Chromatography) is used (Yu, 2008). Advanced techniques such as plant tissue culture, hydroponics, and plant growth in controlled soil environments help in fulfilling the demand for raw material for medicine preparation, as well as rapid cultivation, which helps to save endangered species of plants (Nanaware et al., 2024). Moreover, Nuclear Magnetic Resonance spectroscopy, in conjunction with multivariate data processing, is presently the preferred technique for pharmaco-metabolomics research due to its impartial, non-destructive characteristics and low sample preparation needs (Kumar et al., 2016).

Analytical methods for R & D and quality control of AYUSH products

Any changes in the physical or chemical properties of Ayurvedic medicinal products have been studied using, thermogravimetric analysis (TGA), HPLC, HPTLC differential thermal analysis (DTA), GC-MS, LC-MS and differential scanning calorimetry (DSC) (Pant, 2021). It has also been employed to investigate pre-formulation or drug excipient compatibility. The near-infrared spectroscopy (IR Spectroscopy) technique has been employed to rapidly identify active components, species, unique medicinal formulae, in-process quality control, counterfeit identification, and the discrimination of the geographical origins of plant species. Consequently, the industries have also contributed by identifying and standardizing polyherbal Ayurvedic formulations through these technologies (Pratiwi et al., 2021; Rajani and Kanaki, 2008; Sekar and Vinothkanna, 2019). Industries have implemented the DNA fingerprinting technique, the most recent gold standard instrument, to eliminate plant species adulteration (Luo et al. 2024; Lanubile et al., 2024; Ibrahim et al., 2024). Morell et al. (1995) proved this by identifying intra-generic and intra-specific DNA markers in various Ayurvedic botanicals. Moreover, various advanced techniques such as XRD, AFM, TEM, SEM, and

Energy Dispersive Spectroscopy have been used to estimate and characterize metal and ayurvedic preparations in which metal serves as a carrier for drug delivery, which is highly regarded for a broad range illnesses treatment (Choudhary and Sekhon, 2011). The neutron activation study of calcium, iron, zinc, and mercury has been important in verifying the purity of 'bhasma'. Today, businesses have increasingly embraced the use of microfluidic analytical equipment for drug analysis (Fan et al., 2024).

Thereafter, multidisciplinary research in Ayurveda with biotechnology, chemistry, and pharmacy will result in more accurate results in research and development advancements in the discipline. Biotechnology is the use of the biological system to enhance the quality of life or to refine the processes of living beings (Fan et al., 2024; Ma et al., 2024). There is a substantial gap between biotechnology and the Ayush system of medicine, which encourages multidisciplinary research.

Biotechnology harnesses biological systems and processes to improve or augment the quality of human and living being's life (Eskandar, 2023). The applications of Ayurvedic medicines derived from plants have a wide range of possibilities (Kumar et al., 2017). These include using plant tissue culture to develop improved and disease-resistant plant varieties, enhancing production, diagnosing medicinal plant pathogens, detecting markers of established active principles, exploring pharmacognosy for new drugs, utilizing microbial processes and soil microorganisms, and developing methods for storing and processing crude medicinal materials. Biotechnology is also used to preserve the genetic material of endangered medicinal plant species (Jain et al., 2012; Pence, 1999). Transgenic methods or chemical synthesis can be used on an industrial scale to produce well-defined active principles or those from plants that can't be grown (Darbani et al., 2007). Several factors, including unhindered access to the native gene pool, the pursuit of maximum profit, lack of knowledge of natural herbal plants, the regulatory framework of plant protection, insufficient cultivation, and the conventional methodologies for drug purification, and underutilized gene pool, have all contributed to the growing threat (Katiyar et al., 2023). Biotechnology can significantly contribute to the cataloging and efficient exploitation of germplasm by offering conservation tools like gene banks, tissue cultures, and seed banks. Efficiently managing collection of gene pool and marker-assisted evaluation, removal of redundancy, and identifying the potential member for in-situ and ex-situ conservation. Furthermore, enhancing the quality of current

germplasm through manipulating the genetic makeup by transferring crucial genes to expand the genetic diversity (Sarwat et al., 2012).

Phytochemical Profiling and Standardization: Biotechnological techniques such as metabolomics, proteomics, and genomics enable the comprehensive characterization and standardization of herbal formulations, ensuring consistency in quality and efficacy. Furthermore, to fulfill this need, it is imperative to determine the chemoprofiles of the samples utilizing advanced biotechnological instruments such as TLC, GLC, and HPLC fingerprint profiles (Zahiruddin et al., 2021). Fingerprint profiles such as active principles, chemical markers, and measurement of the marker compound despite its rich heritage and widespread popularity (Rajani and Kanaki, 2008).

Bioprospecting and Drug Discovery: Biotechnology is important in bioprospecting and drug development because it uses genetic engineering, molecular biology, and bioinformatics technologies to investigate natural resources for new chemicals with therapeutic promise. It also involves finding species in varied environments, such as oceans or rainforests, and looking into their genetic makeup to isolate bioactive compounds. The report delves deeply into the flora, traditional usage, and pharmacological relevance of Karanjwa (Caesalpinia bonduc (L.) Roxb), recommending its use as a preventive AYUSH-Unani single medication for COVID-19 management (Husain et al., 2020; Srikanth et al., 2023). It is expected to investigate the plant's botanical qualities, historical usage in traditional medicine, and pharmacological properties related to COVID-19 treatment. The study may shed light on the possible efficacy of Karanjwa as a viral prevention or treatment option, based on both traditional wisdom and modern scientific understanding (Husain et al., 2020). Biotechnology also helps in the production and modification of these molecules for therapeutic development, hence improving their efficacy and safety characteristics. Furthermore, biotech technologies offer high-throughput screening of huge compound libraries and the analysis of biological pathways for target identification and validation, hence easing the drug discovery process. Overall, biotechnology improves the efficiency and effectiveness of bioprospecting and drug discovery activities.

Scope of use of biotechnological tools in the AYUSH system of medicine

In research, biotechnological techniques are employed to enhance various aspects of the AYUSH system of medicine, including research, production, quality control, and efficacy

assessment, for instance, some of these are listed in Table 1. Modern biotechnological techniques used in the AYUSH system of medicine include:

1. **Plant Tissue Culture:** To mitigate the risk of extinction of herbal species and to prevent the mixing of substitutes or adulterants that may compromise the safety and efficacy of herbal preparations. In-situ and ex-situ conservation of endangered plant species that are regarded as essential components of the AYUSH therapeutic system, this program seeks to ensure the continuous supply of high-quality herbs and herbal raw materials (Katiyar et al., 2023). Propagating medicinal plants through tissue culture techniques ensures a consistent and sustainable supply of raw materials regardless of season and cultivation areas (Yoshimatsu, 2008). It also increases secondary metabolite production from medicinal plants for AYUSH medicines (Srivastava et al., 2020). Furthermore, because biological components are so complex, extra steps need to be taken to ensure the quality and safety of homeopathic and ayurvedic medicines (Sen and Chakraborty, 2015; Bandaranayake, 2006). It is important to think carefully about the safety of microbes and viruses, the spread of Spongiform Encephalopathies, and any bad effects that may be caused by chemicals or excipients, depending on the tissue or species they come from. So, among other things, homeopathic medicines must meet quality standards for starting materials and first safe formulas, as well as quality control while they are being made (Sen and Chakraborty, 2017).

Nanotechnology: Developing nanoscale delivery systems to improve the absorption, stability, and targeted delivery of active compounds in AYUSH medicines (Rajendran, 2017). Herbalists have used nanotechnology to create nanostructured formulations that draw on the powerful active ingredients found in medicinal plants, roots, rhizomes, and stem bark, among other portions of the plant (Khan et al., 2022). Natural materials are favored due to their numerous advantages, including the capacity to convey several active constituents via a single carrier, prolong residence time in the body, facilitate a sustained release system, and mitigate side effects (Kumari et al., 2010). Compared to more conventional means of pharmaceutical delivery, the addition of nanotechnology to the engineering of these herbal remedies has many benefits, that includes better site targeting, higher stability, controlled release of active chemicals, and increased bioavailability (Barkat et al., 2020). For instance, improvement in bioavailability was observed with experiments on plant-based nanoparticles of *lamiaceae* family members (Su et al., 2008) and antimicrobial activity was observed with *Ocimum sanctum* extract nanoparticles (Rajendran et al., 2013).

The use of nanocarriers, such as transferosomes, can enhance the bioavailability and targeted delivery of drugs and nutrients applied topically to the skin for the treatment of disease (Fernández-García et al., 2020). Transferosomes serve as nanocarriers applied topically to treat diseases, as they effectively penetrate the lipid lamella of the stratum corneum, facilitating the localized distribution of essential drugs or nutrients to sustain skin function (Celia et al., 2012). Liposome-derived formulation, Herbasec®, and Phytosomes® (phyto-phospholipid complexes for the effective delivery of phytoconstituents) are already available in the market (Barkat et al., 2020). Nanotechnology shows enormous potential in the medical industry, especially for the treatment of cancer (Ullah and Lim, 2022; Mohammadzadeh et al., 2022). For cancer treatment, the use of nanocarriers in conjunction with herbal treatments improves bioavailability, pharmacological activity, and stability while reducing systemic toxicity and minimizing harm to healthy cells while successfully killing cancer cells by achieving optimal concentrations of therapeutic chemicals within the tumor. (Razavi at al., 2024; Ramawat and Arora, 2021).

1. **Pharmacogenomics and pharmacogenetics:** Pharmacogenomics seeks out population-level genetic variants that could account for specific observed reactions to therapeutic drugs (Pirmohamed, 2023). Whereas Garrod first proposed that pharmacogenetics investigates the genetic basis of an unanticipated pharmacological response (Gupta, 2015). However, studying how genetic variations influence individual or population responses to AYUSH treatments, for example, Ayurveda Prakriti Type (Huang et al, 2022) and CYP2C19 Gene Polymorphism Associated with the metabolic variability (Ghodke et al., 2011) which enables personalized medicine approaches. The genetic differences may lead to modulated ADME, efficacy, and toxicity response of individuals because of metabolic processes that could be by pharmacogenetics (Evans, 1999). The genetic variation may lead to polymorphism of receptor, transporter, or enzyme activity of cells that lead to differences in the pharmacodynamics of individual genetics of human beings, and if a drug is provided accordingly better efficacy with low or null toxicity will be there (Lauschke et al., 2024; Anunobi, 2024). The adverse reaction cases for patients will be reduced with tailored drugs with optimum doses for particular genetic constitutions (Molla and Bitew, 2024). According to Vesell identical twins who are 100 % genetically identical show the same result for some drugs as compared to fraternal twins, who share only 50% of genetic constituents (Rahmioğlu and Ahmadi, 2010). Personalized medicine will be in the system if patient care management tests many identified markers of disease for testing rapid detection in patients (Abul-Husn et al,

2014; Ginsburg and McCarthy, 2001). This can be done with genotyping technologies such as RFLP (Jain and Jain, 2021; Kim and Misra, 2007), mass spectrometry (Son et al., 2024), allele-specific PCR (Lee et al., 2016), gene chip technology (Castaldo et al., 2010), and high throughput genotyping using fluorescent dyes.

2. **Biopharmaceuticals:** Developing biologically derived drugs such as recombinant proteins, hormone growth factors, interferons, interleukins, insulin, penicillin G acylase, streptavidin, including recombinant antibodies, and nucleic acid- and genetically engineered cell-based products and vaccines are known as biopharmaceuticals (Lakowitz et al., 2018; Walsh and Walsh, 2022). Biologically derived based on principles of Ayurveda, Unani, Siddha, and Homeopathy are biopharmaceuticals (Sekhon, 2010). A molecular expression of herbal and animal-derived therapeutic substances comes into this category (Madhavan, 2014). Indian Ayurvedic companies such as Ozone Pharmaceuticals, Sami Labs, Hindustan Lever Ltd., etc. have started biopharmaceutical production.

6. Bioinformatics in Ayurveda: Integrating bioinformatics facilitates the elucidation of Ayurvedic principles at a molecular level, aiding in personalized medicine, facilitates analysis of traditional medicine formulations, predicting interactions between bioactive compounds, and understanding their mode of action. Here are several ways in which bioinformatics can contribute to Ayurveda:

(a) Multi-Omics technologies for medicinal and herbal plant Analysis: Bioinformatics tools can be used to analyze the chemical constituents of medicinal plants used in Ayurveda by sequencing and analyzing the genomes of these plants. Research on phenotyping medicinal plants grown in various environments or phases; and categorization and verification through the use of DNA and/or phytochemical markers (Ma et al., 2020). Furthermore, researchers can identify active compounds, understand their interactions, and predict potential therapeutic effects.

Typically, **Genomics** research comprises genetic testing that involves looking for inherited mutations or somatic variations in a particular gene or genes in a patient's sample. Implementing whole exome or genome sequencing in clinical settings necessitates the use of established, robust, and replicable techniques for generating and analyzing sequences. Genome sequencing has the potential for improved diagnostics for rare genetic disorders and variant detection (Bainbridge et al., 2011).

Furthermore, analyzing the genetic makeup of medicinal plants used in Ayurveda, Unani, and Siddha can help identify and understand their active compounds and therapeutic properties. Ayurveda, on the other hand, is an ancient personalized medical system that uses a patient's disease endophenotype, basic constitution, and current health status to determine the right medication and diet regimen. Every individual possesses a unique genetic makeup known as 'Prakriti' also known as precision or personalized medicine (Bhadresha et al., 2020; Sethi et al., 2011). It deals with personalized treatment, which may be possible because of new insights into tridosha made possible by ayurgenomics, the field that combines genomics with Ayurveda (Wallace, 2020; Mukerji, 2023; Sethi et al., 2011). Researchers from the Ministry of Science and CSIR-IGIB in New Delhi theorize that there may be a chance to investigate whether an individual's Prakriti-based characterization has a genetic foundation (Sangeetha and Prasher, 2023). The integration of current genomics with Ayurvedic Prakriti classification methods led to the first identification of the molecular and genomic foundation of the Dosha Prakriti hypothesis. According to genomic research, there were considerable differences in the levels of gene expression amongst the primary Prakriti types, especially those related to blood coagulation, immunity, and cell division. The field of tailored medication development is currently seeing a surge in research into ayurgenomics (Huang et al., 2022). Ayurgenomics provides a genetic understanding and expression of how physiochemical affect the balance between human health and disease. Physiochemical molecules support the complicated physiological pathways, and plants have long been considered therapeutic agents because of their lower toxicity and adverse effects compared to synthetic medications (Bhadresha et al., 2022).

On the other hand, every living/ non-living organism, plant or animal has conserved genomic regions, which helps us to identify the species (Faircloth, 2017). Also, conserved regions are compared to identify the quantitative or qualitative characteristics in them. Different biotechnological techniques which are hybridization-based (RFLP, Satellite) and PCR-based (EST, SCAR, RAPD, DAF, RAMP, AFLP, ISSR, SRAP, SAMPL) are being used to identify the species gene segment of more potential compared to others, that helps in genetic engineering (Sarwat et al., 2012) to enhance or incorporate desired characteristics in plants by gene insertion as a result increased secondary metabolite production (Sreenikethanam et al., 2022).

Transcriptomics research includes three main applications: transcriptome sequencing for gene expression profiling, co-expression network development, and non-coding RNA discovery.

Proteomics- Investigating the protein composition of animal-originated medicine and medicinal plants, as well as herbal formulations to understand their biological activities and mechanisms of action. Protein interactions, protein structure, and quantitative analysis of proteins are involved in proteomics studies (Aslam et al., 2016).

Metabolomics, an innovative method for elucidating metabolic alterations induced by diseases or their treatments, holds significant promise for evaluating the pharmacological and toxicological properties of traditional herbal medicines. Consequently, it is increasingly evolving into a mutually complimentary technology to genomes, transcriptomics, and proteomics for the therapeutic evaluation of pharmaceutical goods such as traditional herbal medicine (Kumar et al., 2016). It can be also employed to investigate animal blood, serum, urine, and tissue fluid profiles to investigate diseases. The pathogenesis of rheumatoid arthritis is complicated and largely unidentified. The serum metabolomics examination indicated changed amounts of many metabolites, including glycine, tyrosine, 3HB, acetate, and acetone, as well as various important amino acids, including lysine, histidine, phenylalanine, threonine, and valine, which were found to have changed amounts in the serum metabolomics analysis (Rastogi et al. 2024).

On the other hand, it can also be employed in qualitative and quantitative investigations of secondary metabolites, elucidation of regulatory controls governing secondary metabolic pathways, and investigation of biotarget identification and therapeutic potential. Furthermore, identifying and quantifying bioactive compounds present in medicinal plants, herbs, and formulations used in AYUSH. New opportunities for drug development research have arisen thanks to metabolomics and metabolomic profiling of medicinal plants and herbal remedies. Thousands of metabolites found in plants used for medical purposes can be identified all at once using metabolomic methods. These also provide credence to the AYUSH and other traditional medical system holistic treatment philosophies and the scientific knowledge of polypharmacology and multicomponent multitarget effects. Studies involving multicomponent herbal medicines frequently assert synergistic effects in both the lab and the clinic. To better understand the biological impacts and uncover the potential mechanism of synergistic actions, omics technologies should be used in the evaluation of herbal and

traditional medicine's mode of action. With these instruments, we can investigate the potential for dereplication, toxicity, and safety prediction of herbal medicines, and formulate complex component extracts followed by standardization (Mosihuzzaman, 2012). According to Ahmad et al. (2022), a system biology approach should incorporate evaluations of network pharmacology.

Kulyal and colleagues evaluated the variation in secondary metabolites in two varieties of Curcuma aromatica Salisb and five varieties of Curcuma longa L. with the help of chemical chromatography- GC-MS and LC-MS techniques (Kulyal et al., 2021).

Similarly, to create a combination formulation, Zahiruddin et al. optimized the ratio of aqueous extracts of Phyllanthus emblica L., Piper nigrum L., Withania somnifera (L.) Dunal, and T. cordifolia (Willd) Miers using response surface technique. The created blend of herbs exhibited noteworthy ability to modulate immunity in mice who were immunosuppressed due to cyclophosphamide. More than 180 metabolites were detected in the metabolomic analysis using an ideal combination of LC-MS. Treatment with a combination of herbal remedies markedly ($p < 0.01$) improved immune cell subsets, including B cells, CD4 cells, CD8 cells, and NK cells (Ahmad et al., 2022).

Plants like Nigella sativa L. and Berberis aristata DC have a long history of medicinal use. The anticancer efficacy of B. aristata and N. sativa was studied in a 7,12-dimethylbenz [a]anthracene (DMBA)-induced mouse model by Mazhar et al. (2021), who also detailed a method for standardizing the two plants. Combining GC-MS metabolomic analyses of essential oils with molecular docking of the two plants' marker chemicals was the method used. Both the N. sativa and B. aristata extracts and their marker chemicals exhibited anticancer efficacy in the study, which did not affect the female mice in any way. They also prevented tumors in mice that were generated by DMBA (Ahmad et al., 2022).

A preservative used in Indian spice combinations, curries, and food preparations is Pseudevernia furfuracea (L.), an epiphytic lichen. Kalra et al., after extracting polyphenols from Pseudevernia furfuracea and passing them through UHPLC/ESI/MS/MS, selected molecules showed anticancerous activity by applying its polyphenols on three different cell lines (Kalra et al., 2022; Ahmad et al., 2022).

A comprehensive method called "metabolomics" can measure all or a significant number of metabolites present in biological fluids, tissues, or cells. Metabolite profiling, metabolic fingerprinting, and focused analysis are three important metabolomics research techniques (Azad and Shulaev, 2019). The omics data integration is important for the mechanistic studies on plant metabolism and the identification of herbs. Furthermore, the workflow is enhanced by the incorporation of computational tools that facilitate quick and accurate processing, high-throughput analyses, and appropriate storage of the omics data. Conversely, the decipherment of secondary metabolic pathways will be significantly facilitated by functional genomics studies, transcriptional regulatory networks, and protein-protein interactions (Ma et al., 2020).

(b) Drug Discovery and Development: Ayurveda relies heavily on herbal formulations for treating various ailments (Lin et al., 2024). Bioinformatics techniques such as molecular modeling, virtual screening, and pharmacophore modeling can aid in the discovery of new bioactive compounds from traditional medicinal plants. This can lead to the development of novel drugs with enhanced efficacy and fewer side effects.

(c) Personalized Medicine: Ayurveda emphasizes individualized treatment approaches based on an individual's constitution or "Prakriti" (Katiyar et al., 2020), Bioinformatics can facilitate the integration of genomic data with Ayurvedic principles to develop personalized treatment strategies. Through the analysis of an individual's genetic composition, researchers can discern genetic differences that may affect illness risk and treatment response (Griñán-Ferré et al., 2024). Global efforts in precision medicine have sparked a revolution in repositories that connect large-scale genomic data to electronic health records, allowing for genomic analysis spanning the entire phenomenon. Numerous of these programs only concentrate on research findings, which has little immediate impact on patients (Wiley et al., 2024).

(d) Disease Diagnosis and Biomarker Discovery: Bioinformatics tools utilize biomarkers for the identification of disease to easily diagnose, predict, and also do prognosis (Lin et al., 2024). By analyzing omics data (genomics, transcriptomics, proteomics, etc.) from patients, researchers can identify molecular signatures associated with specific diseases or conditions mentioned in Ayurvedic texts. This can facilitate early diagnosis and monitoring of diseases (Ogunjobi et al., 2024).

(e) Systems Biology Approach: The field of systems biology takes a comprehensive view of the interplay between the body's many chemical and metabolic processes (Pandkar et al., 2024). Ayurveda views health and disease as a complex interplay of various factors including genetics, environment, lifestyle, and diet (Goyal and Chauhan, 2024)). Bioinformatics offers a systems biology approach to understanding these complex interactions. Integrating multi-omics data with clinical information can provide insights into the underlying mechanisms of diseases and the efficacy of Ayurvedic interventions.

(f) Quality Control of Ayurvedic Products: Bioinformatics tools can be used for quality control and standardization of Ayurvedic products. DNA barcoding and other genomic techniques can help authenticate medicinal plants and detect adulterants, ensuring the safety and efficacy of Ayurvedic formulations (Travadi et al., 2024).

(g) Data Mining from Classical Texts: Ayurvedic texts contain a wealth of knowledge about medicinal plants, formulations, and treatment strategies. With the help of language and bioinformatics tools, knowledge and facts can be gathered in a short time for example databases such as the AYUSH portal, AYUSH clinical case repository, homeopathic clinical case repository database, etc. Data mining facilitates evidence-based research and drug discovery.

Traditional Formulations and Biological Evaluation: Traditional biotechnological techniques i.e. fermentation technology have been helping AYUSH to make its formulations since its origin. Biotechnological assays help assess the safety, efficacy, and mechanisms of action of traditional formulations, validating their therapeutic claims and ensuring patient safety.

7. Synthetic Biology: Synthetic biology, an interdisciplinary field that combines principles from Biotechnology and computer science, offers innovative approaches to elevated levels of medicinal compound production in animals and plants. AYUSH therapies utilize natural products and most of them are secondary metabolites of animal, plant, or microbes derived compounds with pharmacological properties (Bernardini et al., 2018; Newman and Cragg, 2020). However, recent demands for drug production and quantity have increased due to increased resistance to pathogenic microorganisms, and traditional methods of the production of natural medicines are unable to meet these demands. Synthetic biology enables the reconstruction and optimization of biosynthetic pathways in microbial hosts, facilitating

large-scale production of these compounds. For instance, the biosynthesis of artemisinin, an antimalarial drug traditionally extracted from *Artemisia annua*, has been successfully achieved in engineered yeast, ensuring a more reliable and cost-effective supply. Moreover, paclitaxel, tanshinone, breviscapine, noscapine, and thebaine are also metabolically altered for enhanced production. Optimized and transformed organisms can continuously and efficiently synthesize specific target compounds with high yield (Li, et al., 2021). Furthermore, utilizing synthetic biology, researchers can engineer and synthesize innovative substances that replicate or amplify the medicinal properties of conventional AYUSH treatments. This methodology facilitates the formulation of more efficacious medicines with enhanced pharmacokinetic characteristics, potentially resulting in the emergence of novel drug classes derived from traditional medicine (Yan et al., 2023). Additionally, to improve therapeutic efficacy while decreasing toxicity, synthetic biology allows for the exact manipulation of naturally occurring substances. Traditional pharmaceutical substances can have their safety profiles enhanced through biosynthetic pathway engineering, which will increase their acceptance and incorporation into current healthcare systems (Yan et al., 2023). Overuse of natural resources and environmental damage can result from the production and harvesting of medicinal plants for AYUSH. Synthetic biology provides sustainable alternatives by facilitating the manufacture of these chemicals in microbial systems, hence diminishing the necessity for extensive plant cultivation and safeguarding biodiversity (Shokoohi and Attar, 2024). The integration of synthetic biology with traditional AYUSH methodologies facilitates transdisciplinary research, merging old knowledge with contemporary technology. This integration may facilitate the advancement of novel therapeutic tactics and personalized medicine approaches, hence augmenting the worldwide significance and applicability of AYUSH systems (Chauhan et al., 2023).

8. Genetic engineering: The possibilities for combining genetic engineering with conventional medical practices are brought to light by the fact that modern genetic techniques may assist in situating conventional medicine as a viable option for modern customized treatment. The medicinal properties of plants have been enhanced by the application of genetic engineering. Techniques like transgenic approaches have the potential to enhance disease resistance, guarantee the availability of precious medicinal resources, and raise the production and active substance content of medicinal plants.

For instance, Nicotiana tabacum, commonly known as tobacco: Tobacco plants have been altered to generate artemisinic acid (Precursor of artemisinin) and other biopharmaceuticals. This shows that tobacco plants can be used as a biofactory for therapeutic substances. Carica papaya (Papaya) has also been engineered to be resistant to ringspot virus (PRSV). This improvement is mainly meant to increase crop productivity, but it also makes sure that papaya, which is highly prized in traditional medicine for its anti-inflammatory and digestive qualities, is always available. Genetically engineered therapeutic proteins, such as human monoclonal antibodies, have been produced by genetically modified Lemna minor (duckweed), which is another example. It shows promise as a cost-effective biopharmaceutical producer due to its quick growth and ease of cultivation. Nevertheless, the AYUSH community is worried about how genetically modified (GM) crops will affect medicinal plant species, even if these advances have been made. Concerns regarding the potential negative impacts of genetically modified crops on wild kinds of medicinal plants utilized in Ayurvedic treatments have been voiced by the AYUSH ministry. This emphasizes the significance of regulating and carefully considering the integration of genetic engineering with conventional medical systems.

In Ayurveda, about 15-20% of medicines are derived from animal sources. Classical texts like the Charaka Samhita mention nearly 380 different animal substances, including milk, urine, dung, curd, and ghee, especially from cows, which are used for their medicinal properties (Mahawar and Jaroli, 2006). Although transgenic animals have played a significant role in modern medicine by producing therapeutic proteins and studying human diseases, they are not widely used in AYUSH practices. AYUSH systems of medicine have traditionally emphasized natural remedies derived from plants, minerals, and animal products, with an emphasis on holistic health approaches.

However, the expansive domain of biotechnology presents methodologies that may augment AYUSH methods. Advancements in biotechnology can facilitate the growth of medicinal plants, guaranteeing the availability of superior raw materials for Ayurvedic medicines. Moreover, biotechnological techniques can facilitate the standardization and quality assurance of herbal medications, harmonizing ancient practices with contemporary scientific criteria (Chauhan et al., 2023).

The utilization of transgenic animals presents ethical, environmental, and regulatory implications. In India, the Genetic Engineering Appraisal Committee (GEAC) governs the

authorization of genetically engineered organisms for research and development. Although advancements in animal biotechnology, including the cloning of buffalo heifers, have occurred, the application of transgenic animals within the AYUSH system has not been prioritized.

9. Fermentation Technology in AYUSH: Utilizing fermentation technology particularly in the context of preparing herbal medicines, probiotics, and dietary supplements; enhances the bioavailability and potency of herbal extracts, improving their therapeutic outcomes and facilitating their integration into modern healthcare practices. Here's how fermentation techniques are utilized in each of these systems:

a. Ayurveda: Fermentation eliminates the majority of the unwanted sugars from the raw material of the plant, increasing bioavailability and removing adverse effects. Yeast cell walls naturally bind heavy metals and pesticide residues, functioning as a natural cleansing system in the fermentation process (Massoud et al., 2019). This process not only removes pollutants but also reduces the toxicity of some of the plant's harmful components (Sharma et al, 2020). Fermentation actively ruptures the herb's cells, exposing it to the menstruum. Bacteria possess enzymes that aid in the leaching process by breaking down cell walls. Byproducts of fermentation include an active transport mechanism that carries the dissolved components from the plant material to the menstruum. Ayurveda formulations using fermentation are:

Asava and Arishta: Asava and Arishta are Ayurvedic fermented herbal formulations. These are prepared by fermenting medicinal herbs or plant extracts with jaggery, honey, or sugar along with water and certain fermentation-promoting substances like Dhataki (woodfordia fruticosa) (Chaudhary et al., 2011; Sekar and Vinothkanna, 2019). The fermentation process is believed to enhance the bioavailability and efficacy of the active compounds present in the herbs.

b. Yoga and Naturopathy: Yoga is a complementary system of medicine to alleviate physical and mental health conditions (Kochhar and Antony, 2024). Probiotics and fermented foods are recommended to promote gut health, enhance digestion, and boost the immune system (Roopashri et al., 2023).

c. Fermented medicinal herbs in the Unani system of medicine: Arq, also known as distillates, are aqueous distillates obtained by the fermentation of medicinal herbs or aromatic plants. These preparations are commonly used in Unani medicine for their therapeutic properties (Alvi and Saleem, 2024). Arqs are believed to be effective in treating various

health conditions including gastrointestinal disorders, respiratory abnormalities, and skin ailments. Another is Sharbat, a sweet herbal syrup prepared by fermenting fruit juices or extracts with sugar and water. It is commonly used as a refreshing drink and is believed to have cooling and rejuvenating effects on the body.

d. Fermented Formulations in Siddha: Siddha medicine also employs fermentation techniques to prepare herbal formulations (Singla et al., 2024). Fermented herbal drinks and concoctions are used for their therapeutic properties in Siddha medicine. These formulations are believed to improve vitality, strengthen the immune system, and treat various ailments.

e. Fermentation Homeopathy: In homeopathy, mother tinctures are prepared by macerating medicinal herbs or substances in alcohol and allowing them to undergo a fermentation process. The resulting liquid extract contains the active principles of the herb and is used as a base for preparing homeopathic remedies.

8. Animal tissue culture: Testing of Ayurvedic drugs on cell lines reveals molecular pathways, medicinal efficacy, and clinical and pharmacological characteristics for analysis. Cell line studies show that Ayurvedic formulations with bioactive substances such as flavonoids and polyphenols have anti-inflammatory effects by targeting major inflammatory mediators and signaling pathways. Ayurvedic herbs having antioxidant capabilities have been shown to reduce oxidative damage linked to cardiovascular, neurological, and cancer, as confirmed by cell line research. Ayurvedic formulations with herbs like Brahmi and Ashwagandha have shown neuroprotective properties in Alzheimer's and Parkinson's disease cell lines, enhancing neuronal resilience, reducing oxidative stress, and regulating neuroinflammatory pathways. These findings highlight the pharmacological value of Ayurvedic medicine employing advanced techniques, enabling additional study, clinical trials, and integration into mainstream treatments. Moreover, Animals are also a source of AYUSH drugs. Animals that are healthy should only be used to make homeopathic drugs. Substantial potential for novel discoveries exists in future research avenues. The progress in biotechnology, genetics, and pharmacology has the potential to reveal previously unknown bioactive substances derived from ethnobotanical origins, therefore facilitating the creation of innovative treatments for brain health, improving our immune system as well as various other biological disorders (Khanal et al., 2022). Interdisciplinary partnerships among ethnobotanists, pharmacologists, and other scientists have the potential to expedite these findings and convert traditional knowledge into groundbreaking medical applications

(Rahman et al., 2021). The integration of traditional ethnobotanical knowledge with modern science presents significant prospects for the advancement of healthcare (Sebastian, 2024). To fully harness the potential of ethnobotanical substances and their uses in modern medicine, it is crucial to address ethical concerns, guarantee resource conservation, and promote collaborative research (Sheng, 2001; Rao et al., 2024).

Collaborator organizations of Biotechnology and AYUSH

Collaborations between biotechnology and AYUSH (Ayurveda, Yoga and Naturopathy, Unani, Siddha, and Homeopathy) can offer synergistic approaches to healthcare. Some potential collaborator organizations could include research institutes, universities, hospitals, and pharmaceutical companies interested in integrating traditional medicine with modern biotechnological advancements. Examples might include:

1. CSIR-Institute of Genomics and Integrative Biology (IGIB)

CSIR in India has various laboratories and institutes focusing on both biotechnology and traditional medicine research. CSIR-IGIB has launched a biotechnology partnership with AYUSH, Ayurgenomics, which is related to Ayurveda. Prakriti is based on the genome sequence, making it a milestone study in individualized preventive and predictive medicine. Furthermore, other CSIR institutes, such as IHBT, CDRI, CIAMP, NBRI, and IIIM, have conducted studies on traditional knowledge, including conventional medical systems. Moreover, the study was linked to Ayush, which covers medicinal plant types, botanical reference standards, herbal formulations, and phytopharmaceuticals, as well as integrating traditional and modern sciences. (Sattigeri, 2023).

In 2001, the TKDL started as a collaboration between the CSIR and the Dept. of Indian Systems of Medicine and Homeopathy (now Ministry of Ayush) focused on digitizing information related to traditional medicines, and the cooperation continues (Ravishankar and Shukla, 2007). Traditional Knowledge Digital Library (TKDL) to protect Indian Traditional Knowledge (TK). The database currently contains information on about 4.4 lakh formulations from the texts of Ayurveda, Unani, Siddha, and Sowa Rigpa, and Yoga techniques (White et al., 2017).

2. National Institute of Ayurveda (NIA)

NIA conducts research and offers education in Ayurveda, and collaborating with biotechnology institutions could lead to innovative treatment approaches.

3. National Centre for Cell Science (NCCS)

NCCS focuses on cell biology and biotechnology research. Collaborations with AYUSH institutions could explore cellular mechanisms underlying traditional medicine practices. This institute facilitates research on cancer cells, using herbal extract (Gudasi et al., 2024).

4. Indian Institutes of Technology (IITs)

Several IITs have departments or centers dedicated to biotechnology. Partnering with AYUSH establishments could entail joint efforts in interdisciplinary research endeavors, like the Ayurtech initiative at IIT Jodhpur. This project utilizes an AI-powered integrated framework for assessing population and individual health risks, as well as implementing early intervention strategies.

5. NIMHANS, Bengaluru

Integrated therapy based on yoga and ayurveda for a range of neuropsychiatric conditions.

6. Savitribai Phule Pune University

Patent for Ashwagandha as a vaccination adjuvant.

7. Pharmaceutical Companies

Both biotechnology and AYUSH pharmaceutical companies could collaborate to develop new drugs or therapies that combine modern biotechnological approaches with traditional medicine principles.

8. Indian Council of Medical Research (ICMR)

ICMR supports biomedical research in India. Collaborations with AYUSH institutions could focus on clinical trials and validation studies of traditional medicine treatments.

9. Centre for Integrative Medicine and Research (CIMR) – AIIMS

Modern and updated research facilities for Ayurveda and Yoga execute outstanding results for example yoga is a supplement therapy for migraine and recurrent vasovagal syncope.

10. All India Institute of Ayurveda (AIIA)

AIIA is a premier institute for Ayurveda research and education. Partnering with biotechnology organizations could enhance its research capabilities.

11. Institute of Liver and Biliary Sciences in New Delhi

Study on the Effect of Virechana on Gut Microbiota.

12. Indian Institute of Integrative Medicine (IIIM)

IIIM focuses on research in areas like natural products chemistry and biotechnology. Collaborations with AYUSH institutions could explore the development of herbal medicines and biotechnological approaches for drug discovery.

Collaboration with DBT: This initiative utilizes expertise in evidence-based biotechnological therapies aimed at enhancing the quality of life, extending longevity, and mitigating morbidity associated with chronic disorders. Mechanistic studies of Ayurveda therapeutics are emphasized through the use of animal disease models and advanced analytical methods, complemented by data analytical tools. This research collaboration will elucidate the biological mechanisms underlying Ayush therapies, and incorporate innovative integrated treatment strategies.

Collaboration with DST: Collaboration with Ayush, enhances R&D activities with scientific validation of traditional medicine systems. Scientists and medicine practitioners work together and exchange information to refine procedures so that they can get pure products, discover new drugs, and reduce the cost of treatment. The MoU was signed to promote research and get proposals from academic and research institutions whether from government, private, or autonomous institutes and industries.

Collaboration with ICMR: In collaboration with AYUSH, focuses on advancing research in public health, studying diseases specific to certain demographics, and conducting clinical trials of national and international importance, all in adherence to ethical guidelines.

Quality control and standardization: Implementing biotechnological methods such as DNA barcoding and chromatographic fingerprinting to authenticate and standardize herbal ingredients used in AYUSH formulations (Priya et al., 2023; Pant, 2021).

Ministry of AYUSH: It has taken the initiative for AYUSH-based product quality by following GMP guidelines. Ministry of Ayush initiated Ayush Oushadhi Gunvatta even Uttpadan Samvardhan Yojana (AOGUSY), for Enhancing the laws and regulations at both central and state levels, alongside the development of technical human resources and capacity-building initiatives for Ayush pharmaceuticals (Quamri and Malik, 2024).

a) **Pharmacovigilance program (Ayush Suraksha):** Pharmacovigilance Program for Ayurveda, Siddha, Unani, and Homoeopathy (ASU&H) Drugs have been established under the AOGUSY Scheme. Under the Pharmacovigilance initiative for ASU&H drugs, One National Centre, Intermediary Centres, and Peripheral Pharmacovigilance Centres have been established.

b) **Ayush Vertical in CDSCO:** The Ayush vertical was established inside the Central Medications Standard Control Organization on February 5, 2018, to regulate Ayurvedic, Siddha, Unani, and Homeopathy (ASU&H) medications at the central level. AIIA serves as the National Pharmacovigilance Coordination Centre (NPvCC) for the execution of the pharmacovigilance program for ASU & H Drugs.

c) **Pharmacopoeia Commission for Indian Medicine & Homoeopathy (PCIM & H)** has been established as a Subordinate Office of the Ministry of Ayush for developing pharmacopeia standards of ASU & H drugs and to function as the Central Drug Testing cum Appellate.

d) **One Herb, One Standard:** The collaboration between PCIM&H and the Indian Pharmacopoeia Commission (IPC) made a Memorandum of Understanding (MoU) aimed at developing "One Herb-One Standard" because the success of AYUSH drugs is when the quality and purity of the drug are according to the standards.

Role of WHO in herbal medicine

The WHO defines traditional medicine as being the “total of knowledge, skills, and practices based on the theories, beliefs, and experiences that are indigenous to different cultures, which are used to maintain health, as well as to prevent, diagnose, improve, or treat physical and mental illnesses” (Che et al, 2024). Plants, minerals, organic matter, and other therapeutic substances have been employed by humans as living beings for generations before the establishment and spread of modern medicine, and throughout civilization (Kamboj, 2000, Niazi and Monib, 2024; Anand et al., 2024; Picking, 2024).

Challenges and Limitations

Lack of Standardization: Variability in herbal raw materials and processing methods poses challenges to standardization, hindering the reproducibility and quality control of AYUSH formulations (Srivastava and Misra, 2024; Javed et al., 2024).

Ethical and Regulatory Considerations: The ethical implications of bioprospecting and genetic modification in traditional medicine raise concerns about cultural appropriation and biodiversity conservation. Additionally, regulatory frameworks governing the use of biotechnology in AYUSH need to be strengthened to ensure safety and efficacy (Sahu et al., 2024; Srihita et al., 2024).

Knowledge Gap: Bridging the gap between traditional wisdom and modern science requires interdisciplinary collaboration and knowledge exchange, necessitating capacity building and education initiatives (Kochhar et al., 2024). The interface of different domains has a major scope of new findings and the merging of fields of knowledge has a synergistic effect on the progress of the R & D section.

Cost and Accessibility: The high cost of biotechnological interventions and infrastructure may limit their accessibility, especially in resource-constrained settings, underscoring the need for sustainable and inclusive approaches. However, different funds are provided by govt. which can be used for the paid analysis of research samples also several different schemes allow to use of common instrumentation facilities to access the high-cost instruments for research purposes.

R & D status in AYUSH and Biotechnology: Analysis of research in AYUSH and life science/ biotechnology per year from 1996 to 2020 were analyzed to understand the growth in these two sectors during these years are shown in **Figure 1** (Thelwall and Sud, 2022; Abdill and Blekhman, 2019).

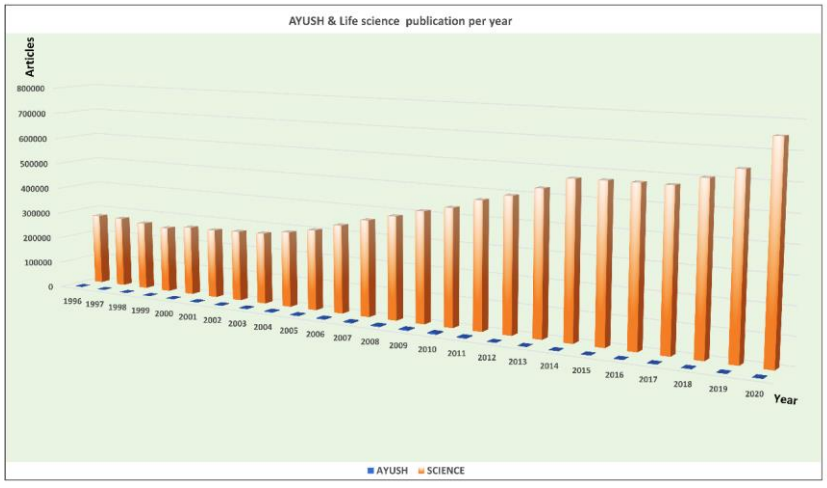

Figure 1: Per year publication in AYUSH medicine from 1996 to 2020 is shown in the blue bar graph and Per year publication of life science publication from 1996 to 2020 is

shown in gradient orange colour bar graph. The intention of showing this data is to compare the research and development in the above two sectors.

Future Directions and Opportunities: The implementation of biotechnology in the AYUSH sector of medicine influences herbal medicine standardization, in which quality and herbal medicine consistency are uniform and constant. It also identifies and quantifies the active-compound signature peak by mass spectrometry and NMR techniques. Because of the constant outcome of the result, the reliability and identification of the therapeutic outcome of a drug is easy. On the other hand, Biotechnological tools are excellent to identify and genetically characterize medicinal plants. This is also useful in the conservation of endangered species whether plant or animal. Through genetic engineering tools, the new breed of living beings with optimized character or existing plant or animal genes can be altered to get medicinal or economic products. It also enhances the existing plant-derived compounds as well as animal-derived compounds. It can also facilitate the creation of novel drugs that can align with AYUSH principals. Moreover, nanotechnology can improve the traditional drug delivery to the target site, which enhances bioavailability, enhances efficacy and reduces side effects. Synthetic biology can help to design new compounds, which can be innovative within the AYUSH framework. Implementation of biotechnology can bring AYUSH and modern medicine to a common ground to share its advantages, enhancing scientific understanding and promoting a more holistic approach to health management.

CONCLUSION

This review gives an overview of the current application of biotechnology in the AYUSH sector of medicine. The incorporation of modern techniques of biotechnology is helping in the standardization of herbal formulations, keeping uniform consistency, and ensuring safety. Scientific validation through biotechnological techniques will improve the global acceptance of the AYUSH system of medicine. By doing it the gap will be reduced between traditional and modern medicine and AYUSH sector limitations will be identified to understand the gap in research of the AYUSH sector. All medicine will be evidence-based. Plants of medicinal use will be conserved. AYUSH can’t grow in isolation, transdisciplinary collaborative work will lead to the advancement of the AYUSH sector of medicine and open opportunities to get funding for innovative drug research by funding bodies.

REFERENCES

1. Abdill, R. J., & Blekhman, R. (2019). Tracking the popularity and outcomes of all bioRxiv preprints. *Elife*, *8*: e45133.
2. Ahmad, N., Qamar, M., Yuan, Y., Nazir, Y., Wilairatana, P., & Mubarak, M. S. (2022). Dietary polyphenols: Extraction, identification, bioavailability, and role for prevention and treatment of colorectal and prostate cancers. *Molecules*, *27*(9): 2831.
3. Ahmad, S., Katiyar, C. K., Ulrich-Merzenich, G. S., & Mukherjee, P. K. (2022). Metabolomics and Ethnopharmacology in the Development of Herbal and Traditional Medicine. *Frontiers in pharmacology*, *13:* 851023.
4. Ardid-Ruiz, A., Ibars, M., Mena, P., Del Rio, D., Muguerza, B., Bladé, C., ... & Suárez, M. (2018). Potential involvement of peripheral leptin/STAT3 signaling in the effects of resveratrol and its metabolites on reducing body fat accumulation. Nutrients, 10(11): 1757.
5. Azad, R. K., & Shulaev, V. (2019). Metabolomics technology and bioinformatics for precision medicine. *Briefings in bioinformatics*, *20*(6): 1957-1971.
6. Bainbridge, M. N., Wiszniewski, W., Murdock, D. R., Friedman, J., Gonzaga-Jauregui, C., Newsham, I., ... & Gibbs, R. A. (2011). Whole-genome sequencing for optimized patient management. *Science translational medicine*, *3*(87): 87re3-87re3.
7. Bajpai, P., Usmani, S., Kumar, R., & Prakash, O. (2024). Recent advances in anticancer approach of traditional medicinal plants: A novel strategy for cancer chemotherapy. *Intelligent Pharmacy*.
8. Barkat, M. A., Harshita, Das, S. S., Beg, S., & Ahmad, F. J. (2020). Nanotechnology-based phytotherapeutics: current status and challenges. *Nanophytomedicine: Concept to Clinic*, 1-17.
9. Bhadresha, K., Patel, M., Brahmbhatt, J., Jain, N., & Rawal, R. (2022). Ayurgenomics: A brief note on ayurveda and their cross kingdom genomics. *International Association of Biologicals and Computational Digest*, *1*(2): 254-258.
10. Bhide, M. M., & Nitave, S. A. (2024). USE OF AYURVEDIC MEDICINES TO TREAT VARIOUS CHRONIC DISEASES.
11. Chatterjee, B., & Pancholi, J. (2011). Prakriti-based medicine: A step towards personalized medicine. *AYU (An International Quarterly Journal of Research in Ayurveda)*, *32*(2): 141-146.
12. Chaudhary, A., Singh, N., Dalvi, M., & Wele, A. (2011). A progressive review of Sandhana kalpana (Biomedical fermentation): An advanced innovative dosage form of

Ayurveda. *AYU (An international quarterly journal of research in Ayurveda)*, *32*(3): 408-417.

13. Chauhan, A., Semwal, D. K., & Joshi, S. K. (2023). An Overview of Biotechnological Applications in Ayurveda: Amalgamation of Modern Techniques and Science. *Current Traditional Medicine*, *9*(1): 23-32.
14. Chopra, A., Saluja, M., & Tillu, G. (2010). Ayurveda–modern medicine interface: A critical appraisal of studies of Ayurvedic medicines to treat osteoarthritis and rheumatoid arthritis. *Journal of Ayurveda and integrative medicine*, *1*(3): 190.
15. Choudhary N, Sekhon BS. An overview of advances in the standardization of herbal drugs. J Pharm Educ Res., 2011; 2(2): 55-70.
16. Coman, N. A., Babotă, M., Nădăan, I., Lucian, R., Ștefănescu, R., Frumuzachi, O., ... & Tanase, C. (2024). Exploring Polyphenols Extraction from Thuja occidentalis L. Bark: Optimization, Phytochemical Profiling, and Biological Evaluation. BioResources, 19(1).
17. Dasgupta, S. C. (2023). Bioactive Compounds from Medicinal Plants and its Therapeutic Uses in the Traditional Healthcare System. In Medicinal Plants: Biodiversity, Biotechnology and Conservation (pp. 525-537). Singapore: Springer Nature Singapore.
18. Evans, W. E., & Relling, M. V. (1999). Pharmacogenomics: translating functional genomics into rational therapeutics. *science*, *286*(5439): 487-491.
19. Ghodke, Y., Joshi, K., & Patwardhan, B. (2011). Traditional medicine to modern pharmacogenomics: Ayurveda Prakriti type and CYP2C19 gene polymorphism associated with the metabolic variability. *Evidence-Based Complementary and Alternative Medicine*, *2011*(1): 249528.
20. Gopal, K. M., Kumar, S., & Gopal, K. U. (2023). Perspectives on Ayush sector: Innovations for future integrative health systems. Journal of Drug Research in Ayurvedic Sciences, 8(1): 86-90.
21. Gupta, P. D. (2015). Pharmacogenetics, pharmacogenomics and ayurgenomics for personalized medicine: a paradigm shift. *Indian journal of pharmaceutical sciences*, *77*(2): 135.
22. Gupta, P. K., Sonewane, K., Rajan, M., Patil, N. J., Agrawal, T., Banerjee, E. R., ... & Kumar, A. (2023). Scientific rationale of Indian AYUSH ministry advisory for COVID-19 prevention, prophylaxis, and immunomodulation. *Advances in Traditional Medicine*, *23*(2): 321-345.

23. Hall, I. H., Starnes Jr, C. O., Lee, K. H., & Waddell, T. G. (1980). Mode of action of sesquiterpene lactones as anti-inflammatory agents. *Journal of pharmaceutical sciences*, *69*(5): 537-543.
24. https://pcimh.gov.in/show_content.php?lang=1&level=1&ls_id=506&lid=6
25. Huang, Z., Chavda, V. P., Bezbaruah, R., Uversky, V. N., P, S., Patel, A. B., & Chen, Z. S. (2022). An ayurgenomics approach: prakriti-based drug discovery and development for personalized care. *Frontiers in Pharmacology*, *13:* 866827.
26. Husain, M. K., Pratap, G. P., Alam, M., Javed, G., & Kazmi, M. H. (2020). Botany, traditional uses and pharmacological importance of Karanjwa (Caesalpinia bonduc (L.) Roxb.): A possible prophylactic AYUSH-Unani single drug for the management of COVID-19. *Int J Herbal Med.*, *8:* 63-9.
27. Iftikhar, A., Aslam, B., Iftikhar, M., Majeed, W., Batool, M., Zahoor, B., ... & Latif, I. (2020). Effect of Caesalpinia bonduc polyphenol extract on Alloxan-induced diabetic rats in attenuating hyperglycemia by upregulating insulin secretion and inhibiting JNK signaling pathway. *Oxidative Medicine and Cellular Longevity*, *2020*(1): 9020219.
28. Javed, D., Dixit, A. K., Anwar, S., & Giri, N. (2024). Exploring the Integration of AYUSH Systems with Modern Medicine: Benefits, Challenges, Areas, and Recommendations for Future Research and Action. *Journal of Primary Care Specialties*, *5*(1): 11-15.
29. Jose, S. P., Ratheesh, M., Sheethal, S., Rajan, S., Saji, S., Narayanan, V., & Sandya, S. (2022). Anti-inflammatory effect of Kaba Sura Kudineer (AYUSH approved COVID-19 drug)-A Siddha poly-herbal formulation against lipopolysaccharide induced inflammatory response in RAW-264.7 macrophages cells. *Journal of Ethnopharmacology*, *283:* 114738.
30. Kalra, R., Conlan, X. A., Gupta, M., Areche, C., Bhat, M., & Goel, M. (2022). Evaluation of the anticancer potential of secondary metabolites from Pseudevernia furfuracea based on epidermal growth factor receptor inhibition. *Natural Product Research*, *36*(24): 6439-6442.
31. Kamboj, V. P. (2000). Herbal medicine. *Current science*, *78*(1): 35-39.
32. Katiyar, C. K., Chakrabarty, A. K., Dubey, S. K., Pandey, P. K., Tumulu, M., & Narwaria, A. (2023). Enhancing quality of Ayush products–Strategies and efforts of the ministry of Ayush and Ayush industry. *Journal of Research in Ayurvedic Sciences*, *7*(Suppl 1): S73-S81.

33. Katiyar, C. K., Hazra, R., & Kanjilal, S. (2020). Correlating Ayurveda and biotechnology: approaches for the 21st century and beyond. In *Animal Biotechnology* (pp. 675-687). Academic Press.
34. Khanal, P., Duyu, T., Patil, B. M., Dey, Y. N., Pasha, I., Wanjari, M., ... & Maity, A. (2022). Network pharmacology of AYUSH recommended immune-boosting medicinal plants against COVID-19. *Journal of Ayurveda and integrative medicine*, *13*(1): 100374.
35. Kochhar, A. M., & Antony, E. (2024). Quality assured Ayush system: Bridging traditional wisdom with modern National Accreditation Board for Hospitals and Health-care Providers (NABH) standards. *International Journal of Ayurveda Research*, *5*(1): 5-10.
36. Kulyal, P., Acharya, S., Ankari, A. B., Kokkiripati, P. K., Tetali, S. D., & Raghavendra, A. S. (2021). Variable secondary metabolite profiles across cultivars of Curcuma longa L. and C. aromatica Salisb. *Frontiers in Pharmacology*, *12:* 659546.
37. Lakowitz, A., Godard, T., Biedendieck, R., & Krull, R. (2018). Mini review: recombinant production of tailored bio-pharmaceuticals in different Bacillus strains and future perspectives. European Journal of Pharmaceutics and Biopharmaceutics, 126: 27-39.
38. Lele, R. D., & Patwardhan, B. (2020). Transiting from pathy-based to people-centered holistic healthcare. *Journal of Ayurveda and Integrative Medicine*, *11*(3): A1.
39. Li, T. (2024). A Chinese model for legal regulation of Gene-Edited endangered animals and plants. *Gene*, 148350.
40. Ma, X., Meng, Y., Wang, P., Tang, Z., Wang, H., & Xie, T. (2020). Bioinformatics-assisted, integrated omics studies on medicinal plants. *Briefings in bioinformatics*, *21*(6): 1857-1874.
41. Madhavan, H. (2014). Innovation system and increasing reformulation practices in the ayurvedic pharmaceutical sector of south India. Asian Medicine, 9(1-2): 236-271.
42. Massoud, R., Hadiani, M. R., Hamzehlou, P., & Khosravi-Darani, K. (2019). Bioremediation of heavy metals in food industry: Application of Saccharomyces cerevisiae. *Electronic Journal of Biotechnology*, *37:* 56-60.
43. Mishra, B., Agarwal, A., George, J. A., Upadhyay, A. D., Nilima, N., Mishra, R., ... & Srivastava, V. P. (2024). Effectiveness of Yoga in Modulating Markers of Immunity and Inflammation: A Systematic Review and Meta-Analysis. *Cureus*, *16*(4).
44. Mohammadzadeh, V., Barani, M., Amiri, M. S., Yazdi, M. E. T., Hassanisaadi, M., Rahdar, A., & Varma, R. S. (2022). Applications of plant-based nanoparticles in nanomedicine: A review. *Sustainable Chemistry and Pharmacy*, *25:* 100606.

45. Morell MK, Peakall R, Appels R, Preston LR, Lloyd HL. DNA profiling techniques for plant variety identification. Aust J Exp Agric., 1995; 35(6): 807–19.
46. Mosihuzzaman, M. (2012). Herbal medicine in healthcare-an overview. *Natural Product Communications*, *7*(6): 1934578X1200700628.
47. Mukerji, M. (2023). Ayurgenomics-based frameworks in precision and integrative medicine: Translational opportunities. *Cambridge Prisms: Precision Medicine*, *1:* e29.
48. Nanaware, J. P., Ghatage, A. A., & Jagtap, A. D. (2024). Optimizing Plant Tissue Culture Techniques for Rapid Propagation of Endangered Medicinal Plants. *NATURALISTA CAMPANO*, *28*(1): 44-51.
49. Nawab, M., & Sherwani, F. (2024). Understanding validation of traditional approaches to health: An analysis of research trends and the need for minimum standards-A systematic review. *Indian Journal of Traditional Knowledge (IJTK)*, *23*(3): 213-223.
50. Nithin, S. A., Belaguli, G., & Mohan, K. (2022). Customized Ayurveda approaches in modulating brain injury: A case report. Journal of Ayurveda Case Reports, 5(2): 68-73.
51. Orhan, I., Kartal, M., Kan, Y., & Şener, B. (2008). Activity of essential oils and individual components against acetyland butyrylcholinesterase. *Zeitschrift fuer Naturforschung C*, *63*(7-8): 547-553.
52. Pant, J. (2021). Review on Standardization of Ayurvedic Medicine. *Journal of Pharmaceutical Research International*, *33*(57A): 194-199.
53. Patil, A. D., Chinche, A. D., Singh, A. K., Peerzada, S. P., Barkund, S. A., Shah, J. N., & Jadhav, A. B. (2019). Ultra high dilutions: A review on in vitro studies against pathogens. *African Journal of Biotechnology*, *18*(13): 275-279.
54. Pratiwi R, Dipadharma RH, Prayugo IJ, Layandro OA. Recent analytical method for detection of chemical adulterants in herbal medicine. Molecules, 2021 Oct 31; 26(21): 6606.
55. Kumar P., S. V., Sandeep, M., Kamal, D., Nishanth, B. C., Megharaj, H. K., Prashith Kekuda, T. R., & Gurucharan, D. N. (2010). Antibacterial and Anthelmintic activity of selected fermented Ayurvedic herbal formulations. *Drug invention today*, *2*(7).
56. Prince, P. S. M., & Roy, A. J. (2013). p-Coumaric acid attenuates apoptosis in isoproterenol-induced myocardial infarcted rats by inhibiting oxidative stress. *International journal of cardiology*, *168*(4): 3259-3266.
57. Priya, K., Dagar, M., Dikshit, M., & Kumar, A. (2023). Herbal Constituents of AYUSH-64 Formulation Modulate Release of Cytokines in TLR7/8-Induced Macrophage-Like Cells. J Clin Exp Pharmacol, 13: 394.

58. Rahman, M. H., Akter, R., & Kamal, M. A. (2021). Prospective function of different antioxidant containing natural products in the treatment of neurodegenerative diseases. CNS & Neurological Disorders-Drug Targets (Formerly Current Drug Targets-CNS & Neurological Disorders), 20(8): 694-703.
59. Rajani, M., & Kanaki, N. S. (2008). Phytochemical standardization of herbal drugs and polyherbal formulations. In *Bioactive molecules and medicinal plants* (pp. 349-369). Berlin, Heidelberg: Springer Berlin Heidelberg.
60. Rajendran, E. S. (2017). Nano pharmacological aspect of homeopathic drugs–A comparative study of different scales of ultra-high dilutions based on HRTEM Analysis and NP characterization of homeopathic drug Natrum muriaticum 6C− CM and LM1− LM30. *Saudi J Med Pharm Sci.*, *3*(2): 89-106.
61. Ramawat, K. G., & Arora, J. (2021). Medicinal plants domestication, cultivation, improvement, and alternative technologies for the production of high value therapeutics: an overview. *Medicinal plants: domestication, biotechnology and regional importance*, 1-29.
62. Randive, D. S., Sayyad, S. F., Bhinge, S. D., & Bhutkar, M. A. (2016). Preparation of Arjunāriṣṭa using microbes isolated from woodfordia fruticosa flowers (dhayati). *Ancient Science of life*, *36*(1): 42-47.
63. Rani P., Jaiswal M., Maurya D. K., Varshney A.K., Sharma N., Tripathi A.K. (2023). A systemic review on comparative study of traditional and modern methods of preparation of ayurvedic medicines. An International Journal of Research in AYUSH and Allied Systems, 10(4): 83-90.
64. Rao, V. U. M., Kumar, S., Sharma, S., Sharma, A., Siddiqui, Z., & Kumar, Y. (2024) Ethnobotanical Insights into Plants Used for Brain Health From Traditional Practices to Modern Applications. Afr. J. Bio. Sc., 6(10): 6660-6670.
65. Ravishankar, B., & Shukla, V. J. (2007). Indian systems of medicine: a brief profile. *African Journal of Traditional, Complementary and Alternative Medicines*, *4*(3): 319-337.
66. Razavi, M. S., Ahmadi, F., Ebrahimnejad, P., Akbarzadeh, A., Farokhrou, M., & Nokhodchi, A. (2024). Harnessing Nanotechnology for Optimized Herbal Cancer Treatment: A Comprehensive Review of Nanoscale Drug Delivery Systems. *Pharmaceutical Sciences*.

67. Roopashri, A. N., Savitha, J., Divyashree, M. S., Mamatha, B. S., Rani, K. U., & Kumar, A. (2023). Indian Traditional Fermented Foods: The Role of Lactic Acid Bacteria. In *Lactobacillus-A Multifunctional Genus*. IntechOpen.
68. Rudra, S., Kalra, A., Kumar, A., & Joe, W. (2017). Utilization of alternative systems of medicine as health care services in India: Evidence on AYUSH care from NSS 2014. PloS one, 12(5): e0176916.
69. Sabu, A., & Haridas, M. (2015). Fermentation in ancient Ayurveda: Its present implications. *Frontiers in Life Science*, *8*(4): 324-331.
70. Sangeetha, K., & Prasher, B. (2023). Ayurgenomics: A Novel Integrative Research Framework of Ayurveda and Genomics towards P5 Medicine. *Journal of Research in Ayurvedic Sciences*, *7*(Suppl 1): S13-S18.
71. Santos-Beneit, F. (2024). What is the role of microbial biotechnology and genetic engineering in medicine?. *MicrobiologyOpen*, *13*(2): e1406.
72. Sarwat, M., Nabi, G., Das, S., & Srivastava, P. S. (2012). Molecular markers in medicinal plant biotechnology: past and present. *Critical reviews in biotechnology*, *32*(1): 74-92.
73. Sattigeri, V. J. (2023). Role of government and research organizations in rejuvenating and re-affirming the value of traditional knowledge systems–AYUSH, as a case in point. *Journal of Research in Ayurvedic Sciences*, *7*(Suppl 1): S55-S59.
74. Seehausen, O., Butlin, R. K., Keller, I., Wagner, C. E., Boughman, J. W., Hohenlohe, P. A., ... & Widmer, A. (2014). Genomics and the origin of species. Nature Reviews Genetics, 15(3): 176-192.
75. Sekar, S., & Vinothkanna, A. (2019). Polyherbal and submerge fermented medicines of Ayurveda: Convergence of tradition with scientific trends and needs. *South African journal of botany*, *121:* 410-417.
76. Sethi, T. P., Prasher, B., & Mukerji, M. (2011). Ayurgenomics: a new way of threading molecular variability for stratified medicine.
77. Sharma, R., Garg, P., Kumar, P., Bhatia, S. K., & Kulshrestha, S. (2020). Microbial fermentation and its role in quality improvement of fermented foods. *Fermentation*, *6*(4): 106.
78. Sheng-Ji, P. (2001). Ethnobotanical approaches of traditional medicine studies: some experiences from Asia. Pharmaceutical biology, 39(sup1): 74-79.
79. Singla, R. K., Singh, D., Verma, R., Kaushik, D., Echeverría, J., Garg, V., ... & Shen, B. (2024). Fermented formulation of Silybum marianum seeds: Optimization, heavy metal analysis, and hepatoprotective assessment. Phytomedicine, 124: 155286.

80. Srikanth, N., Rana, R. K., Jameela, S., Singhal, R., Tripathi, A., Khanduri, S., ... & Dhiman, K. S. (2023). Use of Ayush measures and advocacies by Ayush practitioners and health seekers for the prevention of coronavirus disease-19: Cross-sectional analysis of an application-based data. *International Journal of Ayurveda Research*, *4*(2): 84-92.
81. Srivastava, P., Singh, M., & Chaturvedi, R. (2020). Herbal medicine and biotechnology for the benefit of human health. In *Animal Biotechnology* (pp. 613-629). Academic Press.
82. Thelwall, M., & Sud, P. (2022). Scopus 1900–2020: Growth in articles, abstracts, countries, fields, and journals. *Quantitative Science Studies*, *3*(1): 37-50.
83. Tillu, G. (2018). AYUSH research for New India: Vision and strategies. *Journal of Ayurveda and Integrative Medicine*, *9*(3): 240.
84. Ullah, A., & Lim, S. I. (2022). Plant extract-based synthesis of metallic nanomaterials, their applications, and safety concerns. *Biotechnology and Bioengineering*, *119*(9): 2273-2304.
85. Van Wassenhoven, M., Goyens, M., Capieaux, E., Devos, P., & Dorfman, P. (2018). Nanoparticle characterisation of traditional homeopathically manufactured Cuprum metallicum and Gelsemium sempervirens medicines and controls. *Homeopathy*, *107*(04): 244-263.
86. Wallace, R. K. (2020). Ayurgenomics and modern medicine. *Medicina*, *56*(12): 661.
87. Walsh, G., & Walsh, E. (2022). Biopharmaceutical benchmarks 2022. *Nature Biotechnology*, *40*(12): 1722-1760.
88. White, J. D., O'Keefe, B. R., Sharma, J., Javed, G., Nukala, V., Ganguly, A., ... & Trimble, E. L. (2017). India-United States dialogue on traditional medicine: toward collaborative research and generation of an evidence base. Journal of Global Oncology, 4: 1-10.
89. Wiley, L. K., Shortt, J. A., Roberts, E. R., Lowery, J., Kudron, E., Lin, M., ... & Gignoux, C. R. (2024). Building a vertically integrated genomic learning health system: The biobank at the Colorado Center for Personalized Medicine. *The American Journal of Human Genetics*, *111*(1): 11-23.
90. Yadav, K. D., & Gupta, S. (2022). Role of Science and Technology in Establishing Ayurveda. *Journal of Ayurveda Campus*, *3*(1): 60-68.
91. Yu, L. X. (2008). Pharmaceutical quality by design: product and process development, understanding, and control. Pharmaceutical research, 25: 781-791.

92. Zahiruddin, S., Parveen, A., Khan, W., Parveen, R., & Ahmad, S. (2021). TLC-Based Metabolite Profiling and Bioactivity-Based Scientific Validation for Use of Water Extracts in AYUSH Formulations. Evidence-Based Complementary and Alternative Medicine, 2021(1): 2847440.
93. Arora, S., Bhardwaj, A., Singh, S., Srivastava, S. K., McClellan, S., Nirodi, C. S., ... & Singh, A. P. (2013). An undesired effect of chemotherapy: gemcitabine promotes pancreatic cancer cell invasiveness through reactive oxygen species-dependent, nuclear factor κB-and hypoxia-inducible factor 1α-mediated up-regulation of CXCR4. *Journal of Biological Chemistry*, *288*(29): 21197-21207.
94. De Santana, F. R., de Paula Coelho, C., Cardoso, T. N., Laurenti, M. D., Hurtado, E. C. P., & Bonamin, L. V. (2014). Modulation of inflammation response to murine cutaneous Leishmaniosis by homeopathic medicines: Thymulin 5cH. *Homeopathy*, *103*(04): 275-284.
95. Bigagli, E., Luceri, C., Bernardini, S., Dei, A., Filippini, A., & Dolara, P. (2014). Exploring the effects of homeopathic Apis mellifica preparations on human gene expression profiles. *Homeopathy*, *103*(02): 127-132.
96. Faircloth, B. C. (2017). Identifying conserved genomic elements and designing universal bait sets to enrich them. *Methods in Ecology and Evolution*, *8*(9): 1103-1112.
97. Sreenikethanam, A., Raj, S., Gugulothu, P., & Bajhaiya, A. K. (2022). Genetic engineering of microalgae for secondary metabolite production: Recent developments, challenges, and future prospects. *Frontiers in bioengineering and biotechnology*, *10:* 836056.
98. Department of Science and Technology. MoU signed between Ministry of Ayush and Department of Science and Technology [Internet]. Government of India; [cited 2024 Oct 29]. Available from: https://dst.gov.in/mou-signed-between-ministry-ayush-and-department-science-and-technology.
99. Press Information Bureau. MoU signed between Ministry of Ayush and Indian Council of Medical Research (ICMR) [Internet]. Government of India; 2023 May 11 [cited 2024 Oct 29]. Available from: https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1923378
100. Griñán-Ferré, C., Bellver-Sanchis, A., Guerrero, A., & Pallàs, M. (2024). Advancing personalized medicine in neurodegenerative diseases: The role of epigenetics and pharmacoepigenomics in pharmacotherapy. *Pharmacological Research*, *205*: 107247.

101. Lin, C., Tian, Q., Guo, S., Xie, D., Cai, Y., Wang, Z., ... & Zhang, A. (2024). Metabolomics for clinical biomarker discovery and therapeutic target identification. *Molecules*, *29*(10): 2198.
102. Travadi, T., Sharma, S., Pandit, R., Joshi, C., Joshi, M., & Joshi, P. (2024). Advancing Herbal Product Authentication: A Comprehensive Review Of DNA-Based Approach For Quality Control And Safety Assurance. Educational Administration: Theory and Practice, 30(6 (S)): 15-25.
103. Ogunjobi, T. T., Ohaeri, P. N., Akintola, O. T., Atanda, D. O., Orji, F. P., Adebayo, J. O., ... & Adedeji, O. O. (2024). Bioinformatics Applications in Chronic Diseases: A Comprehensive Review of Genomic, Transcriptomics, Proteomic, Metabolomics, and Machine Learning Approaches. *Medinformatics*.
104. Lin, G., Li, N., Liu, J., Sun, J., Zhang, H., Gui, M., ... & Tang, J. (2024). Identification of key genes as potential diagnostic biomarkers in sepsis by bioinformatics analysis. PeerJ, 12: e17542.
105. Goyal, M. R., & Chauhan, A. (2024). Holistic Approach of Nutrients and Traditional Natural Medicines for Human Health: A Review. *Future Integrative Medicine*, *3*(3): 197-208.
106. Pandkar, P., Kulkarni, S., Bhutada, S., & Navale, L. (2024). ICT and Technological Advances for Ayurveda Education and Practice: Status, Challenges and Scope. *Educational Administration: Theory and Practice*, *30*(5): 12887-12893.
107. Srivastava, S., & Misra, A. (2024). Recent trends in Ayush research: A paradigm shift for developing quality products. *Journal of Drug Research in Ayurvedic Sciences*, *9*(1): 4-7.
108. Sahu, A., Srivastava, N., Jena, D., Singh, A., Kumar, S., & Chauhan, I. (2024). Important Regulatory Guidelines on Natural Products. Current Traditional Medicine, 10(6): 152-172.
109. Srihita, R. H., Goli, G., & Rajya laxmi, M. (2024). Legal and Regulatory Consideration in Healthcare Industry of India. In *Healthcare Industry Assessment: Analyzing Risks, Security, and Reliability* (pp. 171-200). Cham: Springer Nature Switzerland.
110. Kochhar, A. M., & Antony, E. (2024). Quality assured Ayush system: Bridging traditional wisdom with modern National Accreditation Board for Hospitals and Health-care Providers (NABH) standards. International Journal of Ayurveda Research, 5(1): 5-10.

111. Niazi, P., & Monib, A. W. (2024). The role of plants in traditional and modern medicine. Journal of Pharmacognosy and Phytochemistry, 13(2): 643-647.
112. Anand, S., Dhanorya, D., Bajhaiya, M. K., Rahi, A., Kumar, A., Rani, R., & Yadav, S. (2024). A COMPREHENSIVE OVERVIEW ADVANCEMENTS IN PHARMACOVIGILANCE AND HERBAL DRUG DEVELOPMENT.
113. Picking, D. (2024). The global regulatory framework for medicinal plants. In Pharmacognosy (pp. 769-782). Academic Press.
114. Che, C. T., George, V., Ijinu, T. P., Pushpangadan, P., & Andrae-Marobela, K. (2024). Traditional medicine. In *Pharmacognosy* (pp. 11-28). Academic Press.
115. Alvi, M., & Saleem, M. N. (2024). A Systematic Review of Barley (Hordeum vulgare Linn.) in Unani Medicine with Recent Advances. Journal of Drug Delivery & Therapeutics, 14(9).
116. Sebastian, T. (2024). Cell line studies in Ayurveda: Bridging ancient wisdom and modern science. *International Journal of Biological and Pharmaceutical Sciences Archive*, *7*(1): 158-161.
117. National Institute of Ayurveda. (2024, November, 12). About us. *National Institute of Ayurveda*. Retrieved November 12, 2024, from https://www.nia.nic.in/about.html
118. Gudasi, S., Gharge, S., Koli, R., & Kagawad, P. (2024). Exploring In-Silico, In-Vitro Antioxidant, and Cytotoxic Potential of Valerian wallichii by On Cervical Epithelial Carcinoma (HeLa) Cell Lines. Chemistry & Biodiversity, 21(3): e202302072.
119. Quamri, M. A., & Malik, R. (2024). Pharmacovigilance Program of Unani Drugs in India. Bangladesh Journal of Medical Science, 23(3): 632-637.
120. Giratkar, P. R., & Kubde, S. (2024). Review on classical methods and pharmaceutical advancementin preparation of Asva and Arishta. World Journal of Pharmaceutical Research 13(15): 555-563.
121. Vanisree, M., Lee, C. Y., Lo, S. F., Nalawade, S. M., Lin, C. Y., & Tsay, H. S. (2004). Studies on the production of some important secondary metabolites from medicinal plants by plant tissue cultures. Bot. Bull. Acad. Sin, 45(1): 1-22.
122. Zhou, L. G., & Wu, J. Y. (2006). Development and application of medicinal plant tissue cultures for production of drugs and herbal medicinals in China. Natural Product Reports, 23(5): 789-810.
123. Mitchum, M. G., Hussey, R. S., Davis, E. L., & Baum, T. J. (2007). Application of biotechnology to understand pathogenesis in nematode plant pathogens. In *Biotechnology and plant disease management* (pp. 58-86). Wallingford UK: CAB International.

124. Tripathi, L., & Tripathi, J. N. (2003). Role of biotechnology in medicinal plants. *Tropical journal of pharmaceutical research*, *2*(2): 243-253.
125. Ganie, S. H., Upadhyay, P., Das, S., & Sharma, M. P. (2015). Authentication of medicinal plants by DNA markers. *Plant gene*, *4*: 83-99.
126. Phillipson, J. D. (2007). Phytochemistry and pharmacognosy. *Phytochemistry*, *68*(22-24): 2960-2972.
127. Singh, B. K. (2010). Exploring microbial diversity for biotechnology: the way forward. *Trends in biotechnology*, *28*(3): 111-116.
128. Luo, Y., Yang, H., & Tao, G. (2024). Systematic review on fingerprinting development to determine adulteration of Chinese herbal medicines. *Phytomedicine*, 155667.
129. Lanubile, A., Stagnati, L., Marocco, A., & Busconi, M. (2024). DNA-based techniques to check quality and authenticity of food, feed and medicinal products of plant origin: A review. *Trends in Food Science & Technology*, 104568.
130. Ibrahim, M., Detroja, A., Sheth, B. P., Bhadja, P., Sanghvi, G., & Bishoyi, A. K. (2024). Existing status and future advancements of adulteration detection techniques in herbal products. *Molecular Biology Reports*, *51*(1): 151.
131. Fan, R., Wu, J., Duan, S., Jin, L., Zhang, H., Zhang, C., & Zheng, A. (2024). Droplet-based microfluidics for drug delivery applications. *International Journal of Pharmaceutics*, 124551.
132. Fan, L., Ma, S., Li, L., & Huang, J. (2024). Fermentation biotechnology applied to wheat bran for the degradation of cell wall fiber and its potential health benefits: A review. *International Journal of Biological Macromolecules*, 133529.
133. Ma, Q. P. (2024). Biotechnology: Recent Developments, Emerging Trends, and Implications for Business. *Research Anthology on Bioinformatics, Genomics, and Computational Biology*, 335-355.
134. Eskandar, K. (2023). Revolutionizing biotechnology and bioengineering: unleashing the power of innovation. *J Appl Biotechnol Bioeng*, *10*(3): 81-88.
135. Kumar, S., Dobos, G. J., & Rampp, T. (2017). The significance of ayurvedic medicinal plants. *Journal of evidence-based complementary & alternative medicine*, *22*(3): 494-501.
136. Jain, M., Johnson, T. S., & Krishnan, P. (2012). Biotechnological approaches to conserve the wealth of nature: endangered and rare medicinal plant species, a review. *Journal of Natural Remedies*, 93-102.
137. Pence, V. C. (1999). The application of biotechnology for the conservation of endangered plants. In *Plant conservation biotechnology* (pp. 253-276). CRC Press.

138. Darbani, B., Eimanifar, A., Stewart Jr, C. N., & Camargo, W. N. (2007). Methods to produce marker-free transgenic plants. *Biotechnology Journal: Healthcare Nutrition Technology*, *2*(1): 83-90.
139. Yoshimatsu, K. (2008). Tissue culture of medicinal plants: micropropagation, transformation and production of useful secondary metabolites. *Studies in Natural Products Chemistry*, *34:* 647-752.
140. Bandaranayake, W. M. (2006). Quality control, screening, toxicity, and regulation of herbal drugs. Modern phytomedicine: turning medicinal plants into drugs, 25-57.
141. Sen, S., & Chakraborty, R. (2015). Toward the integration and advancement of herbal medicine: a focus on traditional Indian medicine. *Botanics: Targets and Therapy*, 33-44.
142. Sen, S., & Chakraborty, R. (2017). Revival, modernization and integration of Indian traditional herbal medicine in clinical practice: Importance, challenges and future. *Journal of traditional and complementary medicine*, *7*(2): 234-244.
143. Khan, F., Shariq, M., Asif, M., Siddiqui, M. A., Malan, P., & Ahmad, F. (2022). Green nanotechnology: plant-mediated nanoparticle synthesis and application. *Nanomaterials*, *12*(4): 673.
144. Fernández-García, R., Lalatsa, A., Statts, L., Bolás-Fernández, F., Ballesteros, M. P., & Serrano, D. R. (2020). Transferosomes as nanocarriers for drugs across the skin: Quality by design from lab to industrial scale. *International journal of pharmaceutics*, *573*: 118817.
145. Celia, C., Cilurzo, F., Trapasso, E., Cosco, D., Fresta, M., & Paolino, D. (2012). Ethosomes® and transfersomes® containing linoleic acid: physicochemical and technological features of topical drug delivery carriers for the potential treatment of melasma disorders. *Biomedical microdevices*, *14*: 119-130.
146. Su, Y. L., Fu, Z. Y., Zhang, J. Y., Wang, W. M., Wang, H., Wang, Y. C., & Zhang, Q. J. (2008). Microencapsulation of Radix salvia miltiorrhiza nanoparticles by spray-drying. *Powder Technology*, *184*(1): 114-121.
147. Rajendran, R., Radhai, R., Kotresh, T. M., & Csiszar, E. (2013). Development of antimicrobial cotton fabrics using herb loaded nanoparticles. *Carbohydrate polymers*, *91*(2): 613-617.
148. Anunobi, O. (2024). Pharmacogenomics as a tool in addressing genetic variation-dependent adverse drug reactions.

149. Lauschke, V. M., Zhou, Y., & Ingelman-Sundberg, M. (2024). Pharmacogenomics beyond single common genetic variants: the way forward. *Annual Review of Pharmacology and Toxicology*, *64*(1): 33-51.
150. Molla, G., & Bitew, M. (2024). Revolutionizing Personalized Medicine: Synergy with Multi-Omics Data Generation, Main Hurdles, and Future Perspectives. *Biomedicines*, *12*(12): 2750.
151. Rahmioğlu, N., & Ahmadi, K. R. (2010). Classical twin design in modern pharmacogenomics studies. *Pharmacogenomics*, *11*(2): 215-226.
152. Ginsburg, G. S., & McCarthy, J. J. (2001). Personalized medicine: revolutionizing drug discovery and patient care. *TRENDS in Biotechnology*, *19*(12): 491-496.
153. Abul-Husn, N. S., Owusu Obeng, A., Sanderson, S. C., Gottesman, O., & Scott, S. A. (2014). Implementation and utilization of genetic testing in personalized medicine. *Pharmacogenomics and personalized medicine*, 227-240.
154. Jain, K. K., & Jain, K. K. (2021). Molecular diagnostics in personalized medicine. *Textbook of Personalized Medicine*, 39-101.
155. Kim, S., & Misra, A. (2007). SNP genotyping: technologies and biomedical applications. *Annu. Rev. Biomed. Eng.*, *9*(1): 289-320.
156. Son, A., Kim, W., Park, J., Park, Y., Lee, W., Lee, S., & Kim, H. (2024). Mass Spectrometry Advancements and Applications for Biomarker Discovery, Diagnostic Innovations, and Personalized Medicine. *International Journal of Molecular Sciences*, *25*(18): 9880.
157. Lee, H. B., Schwab, T. L., Koleilat, A., Ata, H., Daby, C. L., Cervera, R. L., ... & Clark, K. J. (2016). Allele-specific quantitative PCR for accurate, rapid, and cost-effective genotyping. *Human gene therapy*, *27*(6): 425-435.
158. Castaldo, G., Lembo, F., & Tomaiuolo, R. (2010). Molecular diagnostics: between chips and customized medicine. *Clinical Chemistry and Laboratory Medicine*, *48*(7): 973-982.
159. Pirmohamed, M. (2023). Pharmacogenomics: current status and future perspectives. *Nature Reviews Genetics*, *24*(6): 350-362.
160. Aslam, B., Basit, M., Nisar, M. A., Khurshid, M., & Rasool, M. H. (2016). Proteomics: technologies and their applications. *Journal of chromatographic science*, 1-15.
161. Rastogi, S., Verma, A., Trivedi, R., Shukla, A., & Kumar, D. (2024). Clinical metabolomics investigation of rheumatoid arthritis patients receiving ayurvedic whole system intervention. *Journal of Ayurveda and Integrative Medicine*, *15*(4): 101009.

162. Sekhon, B. S. (2010). Biopharmaceuticals: an overview. *Thai Journal of Pharmaceutical Sciences*, *34*(1).
163. Kumar, D., Rawat, A., Dubey, D., Kumar, U., Keshari, A. K., Saha, S., & Guleria, A. (2016). NMR based Pharmaco-metabolomics: An efficient and agile tool for therapeutic evaluation of Traditional Herbal Medicines. *arXiv preprint arXiv,1602.02492*.
164. Li, C. Q., Lei, H. M., Hu, Q. Y., Li, G. H., & Zhao, P. J. (2021). Recent advances in the synthetic biology of natural drugs. Frontiers in Bioengineering and Biotechnology, 9: 691152.
165. Yan, X., Liu, X., Zhao, C., & Chen, G. Q. (2023). Applications of synthetic biology in medical and pharmaceutical fields. Signal transduction and targeted therapy, 8(1): 199.
166. Shokoohi, M., & Attar, T. (2024). Biomanufacturing for a Sustainable Future: Unleashing the Potential of Biotechnology in Pharmaceutical Raw Material Production. *International Journal of New Findings in Health and Educational Sciences (IJHES)*, *2*(2): 142-153.
167. Chauhan, A., Semwal, D. K., & Joshi, S. K. (2023). An Overview of Biotechnological Applications in Ayurveda: Amalgamation of Modern Techniques and Science. Current Traditional Medicine, 9(1): 23-32.
168. Mahawar, M. M., & Jaroli, D. P. (2006). Animals and their products utilized as medicines by the inhabitants surrounding the Ranthambhore National Park, India. Journal of Ethnobiology and Ethnomedicine, 2: 1-5.
169. Chauhan, A., Semwal, D. K., & Joshi, S. K. (2023). An Overview of Biotechnological Applications in Ayurveda: Amalgamation of Modern Techniques and Science. *Current Traditional Medicine*, *9*(1): 23-32.
170. Genetic Literacy Project. (n.d.). *India – Animals*. Retrieved December 21, 2024, from https://crispr-gene-editing-regs-tracker.geneticliteracyproject.org/india-animals/
171. Mazhar, M., & Agrawal, S. S. (2021). Standardization of Berberis aristata DC and Nigella sativa L. using HPTLC and GCMS and their antineoplasia activity in 7, 12-dimethylbenz [a] anthracene-induced mouse models. *Frontiers in Pharmacology*, *12*: 642067.