Journal of Proteomics and Genomics Research

Proteomic and Genomic Techniques in Medical Research: Applications in Cancer, Diagnostics, and Personalized Medicine

Oghenetega E. Imiruaye[1,*], Liasu Ogunkanmi[2]

[1]Postdoctoral Fellow, Molecular Biology, Henry E. Riggs School of Applied Life Sciences, Keck Graduate Institute, Claremont, CA, USA.

[2]Professor of Molecular Genetics, Department of Cell Biology and Genetics, University of Lagos, Akoka, Lagos, Nigeria.

Review Article

Open Access &

Peer-Reviewed Article

DOI:10.14302/issn.2326-0793.jpgr-25-5573

Corresponding author:

Oghenetega E. Imiruaye, Postdoctoral Fellow, Molecular Biology, Henry E. Riggs School of Applied Life Sciences, Keck Graduate Institute, Claremont, CA, USA.

Keywords:

PCR, Molecular Diagnostics, Electrophoresis, Gene editing, Genotyping

Received: June 03, 2025

Accepted: June 19, 2025

Published: November 07, 2025

Academic Editor:

Anubha Bajaj, Consultant Histopathologist, A.B. Diagnostics, Delhi, India

Citation:

Oghenetega E. Imiruaye, Liasu Ogunkanmi (2025) Proteomic and Genomic Techniques in Medical Research: Applications in Cancer, Diagnostics, and Personalized Medicine. Journal of Proteomics and Genomics Research - 2(4):1-15. https://doi.org/10.14302/issn.2326-0793.jpgr-25-5573

Abstract

Advancements in proteomic and genomic technologies have transformed molecular biology by enabling comprehensive analysis of biological systems at the molecular level. This literature review explores the evolution, methodologies, and practical applications of key proteomic and genomic techniques. In proteomics, tools such as two-dimensional electrophoresis, mass spectrometry, Western blotting, Edman degradation, and functional protein microarrays have facilitated high-throughput protein identification, post-translational modification analysis, and biomarker discovery. Similarly, genomic methodologies like PCR, recombinant DNA technology, gel electrophoresis, and Southern blotting have revolutionized gene detection, manipulation, and expression profiling. The review also highlights the interdisciplinary impact of these technologies across clinical diagnostics, oncology, autoimmune disorders, infectious disease surveillance, cardiovascular research, and personalized nutrition. Integrative approaches combining proteomics and genomics are enabling the discovery of novel therapeutic targets, improving disease classification, and advancing precision medicine. Despite current limitations, such as the absence of amplification techniques for proteins and challenges in data interpretation, ongoing innovations promise to bridge these gaps. This synthesis underscores the pivotal role of molecular techniques in deepening our understanding of human biology and accelerating biomedical advancements for improved healthcare outcomes.

Introduction

Proteomics, the comprehensive study of all proteins expressed by a genome, cell, tissue, or organism, has emerged as a critical field in post-genomic biology. Coined in the mid-1990s to mirror the term “genomics,” proteomics transcends simple comparison by revealing a far more intricate biological layer. While genomics offers a relatively stable blueprint of potential biological function, proteomics captures the dynamic, context-specific execution of these genetic

instructions. Proteins undergo a wide array of post-translational modifications and are influenced by environmental signals, cellular state, and developmental stage, making the proteome a constantly shifting molecular landscape[1, 2]. The origins of proteomics can be traced to 1975, when scientists first used two-dimensional polyacrylamide gel electrophoresis (2D-PAGE) to separate complex protein mixtures in E. coli, mouse, and guinea pig models [3]. Although these techniques allowed high-resolution protein separation, early researchers were hampered by an inability to accurately identify these proteins. The advent of Edman degradation in the 1950s provided a method for N-terminal sequencing, which was revolutionary at the time but inherently slow and limited to pure protein samples4. The 1980s and 1990s marked a turning point with the development of microsequencing, which increased Edman sequencing sensitivity to the picomole range and enabled protein identification directly from 2D gels[3]. However, the real paradigm shift came with the integration of mass spectrometry (MS) into proteomic workflows. Soft ionization methods such as MALDI (Matrix-Assisted Laser Desorption/Ionization) and ESI (Electrospray Ionization) allowed high-throughput, sensitive, and accurate identification of proteins from even minute sample quantities[5]. The development of tandem MS (MS/MS) and database-searching algorithms turned mass spectrometry into a cornerstone of modern proteomics, rendering Edman degradation nearly obsolete for large-scale studies[6].

These technological advancements have not only enabled qualitative protein identification but also quantitative proteomics, where isotope labeling and spectral counting allow comparisons across different experimental conditions[7]. Functional proteomics further expands this scope by studying protein–protein interactions, post-translational modifications, and pathway dynamics, contributing valuable insights into disease mechanisms, drug development, and biomarker discovery[8]. In contrast, genomics focuses on the study of the genome, the complete set of an organism's DNA, including gene sequencing, structure, function, and regulation. The Human Genome Project (HGP), initiated through a collaborative effort by the NIH and DOE, catalyzed this field by successfully sequencing the entire human genome. The HGP also advanced the study of model organisms, developed new computational and storage techniques, and addressed ethical and legal concerns surrounding genetic data[9]. However, knowing the genome alone does not reveal how biological systems behave in real time. The genome provides the potential, but the proteome reflects reality, the actual functional molecules at work within the cell. This fundamental distinction is why proteomics is considered not just a successor to genomics, but its indispensable complement[10]. Together, genomics and proteomics create a systems-level understanding of life, integrating static genetic potential with dynamic biochemical execution.

Proteomic Methods

Proteomic analysis encompasses a wide range of techniques designed to isolate, separate, identify, and quantify proteins within complex biological samples. These methods are critical for investigating disease pathogenesis, identifying biomarkers, and understanding cellular functions. This review explores five key proteomic techniques in detail: 2D electrophoresis, mass spectrometry, ion exchange chromatography, size exclusion chromatography, and Western blotting.

Two-Dimensional (2D) Protein Electrophoresis

Two-dimensional gel electrophoresis (2-DE) is a foundational technique in proteomics, renowned for its ability to resolve thousands of proteins in a single gel. It separates proteins based on two independent parameters: isoelectric point (pI) and molecular weight. In the first dimension, proteins are subjected to isoelectric focusing (IEF), where they migrate along a pH gradient until reaching a pH corresponding to their pI, where their net charge is zero. In the second dimension, sodium dodecyl sul-

fate polyacrylamide gel electrophoresis (SDS-PAGE) is applied perpendicularly, separating proteins based on their size[11]. The resulting 2D protein "maps" are highly reproducible and enable comparative proteomic analysis. Differential spots observed between samples, such as disease vs. control, can be excised and subjected to mass spectrometric analysis for identification. While 2-DE has limitations in detecting hydrophobic, high-molecular-weight, or very low-abundance proteins, it remains integral in the early phases of protein discovery and biomarker identification[12].

Mass Spectrometry (MS)

Mass spectrometry has emerged as the cornerstone of modern proteomics. This technique measures the mass-to-charge ratio (m/z) of ionized peptides or intact proteins, facilitating their identification and structural characterization. Proteins are typically digested into peptides (e.g., using trypsin), which are then ionized using soft ionization methods like Matrix-Assisted Laser Desorption/Ionization (MALDI) or Electrospray Ionization(ESI)[13]. MS-based protein identification usually follows two major approaches:

- Peptide Mass Fingerprinting (PMF): The masses of the generated peptides are measured and compared to theoretical peptide masses derived from protein databases.
- Tandem Mass Spectrometry (MS/MS): Selected peptides are fragmented, and their fragmentation patterns provide sequence information used for database searching and de novo sequencing.

The sensitivity of MS is now so advanced that proteins present in femtomolar concentrations can be detected. Coupling MS with liquid chromatography (LC-MS/MS) allows for automated, high-throughput proteomic workflows and is indispensable in systems biology, drug discovery, and biomarker validation[14].

Ion Exchange Chromatography (IEC)

Ion exchange chromatography is a technique that separates proteins based on their net surface charge. Proteins contain both positively and negatively charged amino acid residues, and the net charge at a given pH determines their interaction with charged resin in the chromatography column. Depending on whether anion or cation exchange resins are used, proteins with opposite charges bind to the resin and are later eluted by changing the ionic strength or pH of the buffer[15]. IEC is highly valued for its scalability, affordability, and compatibility with protein purification protocols. It can be used as a standalone method or as a preparatory step before more sensitive techniques like MS. For instance, one -step anion exchange chromatography has been successfully used to purify recombinant proteins such as Helicobacter pylori Neutrophil Activator Protein (HP-NAP), an important candidate for vaccine development[16].

Size Exclusion Chromatography (SEC)

Size exclusion chromatography (SEC), also known as gel filtration chromatography, separates proteins based on their hydrodynamic volume (or apparent size) as they pass through a porous matrix. Larger proteins elute first because they cannot enter the pores, while smaller molecules are delayed due to their penetration into the gel's pores. SEC is non-destructive and ideal for analyzing protein complexes under native conditions. It is often used in combination with other techniques such as ion exchange chromatography and MS in multidimensional proteomic workflows (16). Native SEC-MS systems allow for the identification and characterization of protein aggregates, oligomers, and intact complexes with high resolution and minimal sample alteration[17].

Western Blotting

Western blotting is a widely used technique for the detection and semi-quantitative analysis of specific proteins within complex mixtures. The process involves three key steps: separation of proteins via SDS -PAGE, transfer onto a membrane (typically nitrocellulose or PVDF), and detection using specific antibodies conjugated to enzymes or fluorophores. The strength of Western blotting lies in its specificity and its ability to detect proteins even at low abundance. It has broad applications in diagnostics, immunology, and virology. For example, it is extensively used to determine seroprevalence of viral infections, such as Herpes Simplex Virus Type 2, by detecting virus-specific antibodies in patient sera[18]. While Western blotting is limited in throughput and quantification compared to MS-based methods, it remains essential for validating proteomic findings and for clinical biomarker detection.

Edman Sequencing

Edman sequencing, developed by Pehr Edman in the mid-20th century, is a foundational method for determining the amino acid sequence of peptides by sequentially cleaving N-terminal residues. The technique involves the reaction of phenyl isothiocyanate with the amino-terminal residue to form a phenyl thiocarbamoyl derivative, which is then cleaved under acidic conditions to produce a phenyl thiohydantoin (PTH) amino acid that can be identified chromatographically[19]. Although Edman degradation has largely been supplemented by mass spectrometry in high-throughput proteomics, it remains a valuable method for confirming N-terminal sequences, validating post-translational modifications, and quality control of biopharmaceuticals[20]. Recent advances, including microfluidic chip-based sequencing and isotopically labeled reagents, have improved sensitivity to the subfemtomole range[20]. Its application has extended into microbiology as well, for example, in identifying signal peptides responsible for acid resistance in Brucella suis, aiding in understanding pathogenic survival strategies in macrophages[21].

Functional Protein Microarrays

Functional protein microarrays (fPMs) are powerful high-throughput tools that enable the systematic investigation of protein functions, including protein–protein, protein–DNA, protein–lipid, and protein–small molecule interactions. These arrays are constructed using purified proteins immobilized on solid surfaces and interrogated with various probes or ligands[22]. The first notable use of fPMs was in yeast to investigate the substrate specificity of protein kinases, establishing proof-of-concept for functional proteome profiling[23].This technology has since evolved to cover thousands of proteins. For instance, a large-scale protein interaction network was characterized in Arabidopsis thaliana, identifying key calmodulin-like proteins and their substrates, highlighting the technique's relevance in plant signaling pathways[24]. fPMs offer an exceptional platform for drug discovery and biomarker identification due to their ability to capture complex biochemical interactions under native conditions.

Sodium Dodecyl Sulfate Polyacrylamide Gel Electrophoresis (SDS-PAGE)

SDS-PAGE is an electrophoretic technique that separates proteins primarily based on molecular weight. Proteins are denatured by sodium dodecyl sulfate (SDS), a detergent that imparts a uniform negative charge, thereby allowing separation solely on size through a polyacrylamide matrix when an electric field is applied [25]. SDS-PAGE is frequently used as a preparatory or diagnostic step in proteomics, facilitating protein purity assessment, molecular weight estimation, and precursor analysis for mass spectrometry. It is also instrumental in veterinary microbiology, where protein profiling of closely related pathogens, such as Mycoplasma bovis and M. agalactiae, enables differential diagnosis and epidemiological monitoring[26]. The adaptability and resolution of SDS-PAGE continue to make it a stand-

ard in protein science, especially in conjunction with Western blotting and in-gel digestion protocols.

X-ray Crystallography

X-ray crystallography is the gold standard for elucidating the three-dimensional structure of proteins at atomic resolution. Crystallized protein samples are bombarded with X-rays, and the resulting diffraction patterns are computationally transformed into electron density maps, allowing structural modeling of amino acid residues and ligands[27]. This technique has profound implications in structural biology and drug design, offering mechanistic insights into enzyme function, protein-nucleic acid complexes, and antigen-antibody interactions. It has been extensively employed in virology to study capsid architecture, replication enzymes, and viral-host protein interactions. Despite its requirement for high-purity crystals and labor-intensive sample preparation, the high precision of crystallographic data makes it indispensable in understanding functional biology and rational drug design[27].

Enzyme-Linked Immunosorbent Assay (ELISA)

ELISA is a highly sensitive immunoassay technique used for the detection and quantification of antigens or antibodies in complex mixtures. It involves immobilizing an antigen or antibody on a solid surface, followed by incubation with an enzyme-linked detection antibody, and subsequent colorimetric or fluorometric readout based on substrate conversion[28]. ELISA is ubiquitous in diagnostics, including infectious diseases, autoimmune disorders, and cancer biomarker screening. A notable application includes the differentiation of Mycobacterium avium subsp. paratuberculosis from other strains based on surface antigen reactivity in serum samples[29]. Because of its scalability, specificity, and adaptability, ELISA remains central to both clinical and research laboratories in quantifying immune responses and monitoring disease progression.

Genomic Methods

Polymerase Chain Reaction (PCR)

Polymerase Chain Reaction (PCR) is a revolutionary genomic technique that allows for the exponential amplification of specific DNA sequences in vitro. It was invented by Kary Mullis in 1983, and it fundamentally transformed molecular biology, earning Mullis the Nobel Prize in Chemistry in 1993. The method's core principle lies in the repetitive cycling through three thermal steps, denaturation, annealing, and extension, each with specific biochemical significance[30].

- Denaturation: The double-stranded DNA is heated to approximately 94–96°C, which causes the hydrogen bonds between base pairs to break, resulting in single-stranded DNA templates.
- Annealing: The temperature is then lowered to around 50–65°C, allowing specific primers (short DNA fragments complementary to the target sequence) to hybridize to the template.
- Extension: At an optimal temperature of 72°C, the heat-stable DNA polymerase, commonly Taq polymerase, extends the primers by adding nucleotides in a sequence-specific manner.

This three-step cycle is repeated typically 25–35 times, leading to a geometric amplification of the target DNA. The specificity and high yield of PCR have rendered it indispensable in various applications, including gene cloning, mutation detection, diagnostics, forensics, and evolutionary biology[31, 32]. Furthermore, several adaptations of the PCR method have been developed, including: Reverse Transcription PCR (RT-PCR) for studying gene expression by converting RNA into cDNA, Quantitative PCR (qPCR) for real-time amplification and quantification of nucleic acids, Digital PCR for ultra-sensitive detection and quantification and, High-Fidelity PCR for applications requiring low

error rates, utilizing enzymes like Pfu polymerase[33]. PCR's evolution continues with recombinant polymerases such as Pfu-Sso7d, offering enhanced fidelity and processivity[34].

Recombinant DNA Technology

Recombinant DNA (rDNA) technology is a foundational technique in molecular genetics that enables scientists to isolate, manipulate, and recombine DNA sequences from different sources. The method relies heavily on the action of two types of enzymes:

Restriction endonucleases, which cleave DNA at specific recognition sites, generate fragments with "sticky" or "blunt" ends. DNA ligases which covalently join DNA fragments to form stable recombinant molecules. These fragments are typically inserted into cloning vectors such as plasmids, which can autonomously replicate in a host organism, commonly Escherichia coli. The resulting recombinant DNA molecules are introduced into the host via transformation, and all progeny from a single transformed cell, called a clone, carry the same recombinant construct[35].

Recombinant DNA technology underpins genetic engineering, gene therapy, vaccine production, and synthetic biology. For example, genetically engineered insulin is produced by inserting the human insulin gene into E. coli, which then express the protein in large quantities. Moreover, this technology is used in the creation of genetically modified organisms (GMOs) and the development of CRISPR-based genome editing. In recent advances, PCR has been integrated into recombinant DNA workflows, enabling site-directed mutagenesis, in vitro recombination, and rapid cloning without reliance on traditional enzymatic digestion[36, 37]. Advanced applications such as recombinant circle PCR (RCPCR) allow for the precise engineering of plasmids with high efficiency and low error rates[38].

Gel Electrophoresis

Gel electrophoresis is a foundational technique in molecular biology used to separate nucleic acid fragments based on size, charge, and conformation. Because DNA molecules are uniformly negatively charged due to their phosphate backbone, they migrate through a gel matrix toward the anode (positive electrode) when subjected to an electric field. The rate at which DNA fragments move is inversely proportional to their length; smaller fragments migrate faster and farther than larger ones[39]. The two main types of gel used are agarose and polyacrylamide. Agarose gels are ideal for separating DNA fragments ranging from 100 base pairs to 25 kilobases. The concentration of agarose (typically 0.5–3%) determines the pore size of the gel, affecting the resolution. Polyacrylamide gels, on the other hand, offer higher resolution and are often used for fragments less than 500 base pairs, such as in DNA sequencing or protein SDS-PAGE applications[40].Once electrophoresis is complete, the gel is typically stained with ethidium bromide, a molecule that intercalates between DNA base pairs and fluoresces under ultraviolet (UV) light. Newer and less toxic alternatives, such as SYBR Safe and GelRed, provide similar visualization with improved safety profiles[41].

Gel electrophoresis is critical not only for analytical purposes, such as verifying PCR amplification, assessing DNA integrity, and genotyping, but also as a preparatory step for downstream techniques, including Southern blotting, cloning, and DNA extraction for sequencing. Variants such as pulsed-field gel electrophoresis (PFGE) are employed to separate very large DNA molecules (up to megabases), such as chromosomal DNA, by altering the direction of the electric field periodically[42].

Southern Blotting

Southern blotting is a seminal nucleic acid hybridization technique that allows the detection of specific DNA sequences within a complex mixture. Developed by Edwin Southern in 1975, it integrates electrophoresis, membrane transfer, and hybridization with a labeled probe to achieve precise molecular

diagnostics and gene mapping[43].

Procedure Overview

- Restriction Digest and Electrophoresis: Genomic DNA is digested with restriction enzymes into fragments of varying lengths. These are separated using agarose gel electrophoresis.
- Denaturation: The gel is soaked in an alkaline solution (e.g., NaOH) to denature the double-stranded DNA into single strands.
- Transfer: The single-stranded DNA is transferred to a nylon or nitrocellulose membrane via capillary action, vacuum transfer, or electroblotting, preserving the spatial separation of bands.
- Fixation: The DNA is covalently linked to the membrane via UV cross-linking or baking.
- Hybridization: A labeled single-stranded DNA or RNA probe, complementary to the target sequence, is incubated with the membrane under optimized temperature and salt conditions to allow specific hybridization.

Detection: Hybridized probes are detected using radioactive, fluorescent, or chemiluminescent labels. Autoradiography or digital imaging is used to visualize signal bands that correspond to DNA fragments containing the target sequence [44].

Southern blotting has been instrumental in a wide range of genomic applications, such as:

- Gene mapping and cloning: Determining the presence, size, and arrangement of genes.
- Detection of mutations: Identifying insertions, deletions, or rearrangements in genetic diseases such as thalassemia or sickle-cell anemia[45].
- Verification of transgenic organisms: Confirming successful gene insertions in genetically modified plants or animals.
- Restriction fragment length polymorphism (RFLP) analysis: Historically used in forensic identification and paternity testing.

Although Southern blotting is now partially supplanted by PCR-based techniques and next-generation sequencing (NGS), it remains a gold-standard method in situations requiring high specificity and structural analysis of DNA[46].

Applications of Genomic and Proteomic Techniques

The advancement of genomic and proteomic technologies has revolutionized the landscape of biomedical research, offering a more integrative view of molecular biology. These methodologies provide invaluable tools for identifying disease biomarkers, understanding molecular pathogenesis, classifying tumors, and enabling personalized medicine. By combining the information encoded within genes (genomics) with the functional insights offered by proteins (proteomics), researchers are now better equipped to decipher complex biological systems and develop more targeted diagnostic and therapeutic strategies[47].

Screening

Screening is one of the most critical early applications of genomic and proteomic tools. Traditional methods, such as cytology-based Pap smears for cervical cancer, are now being supplemented with molecular testing for high-risk human papillomavirus (HPV) DNA, enhancing sensitivity and predictive value[48]. In proteomics, high-throughput screening platforms such as mass spectrometry and anti-

body-based arrays have enabled the identification of novel protein biomarkers in body fluids. This facilitates non-invasive screening for various malignancies, including ovarian, breast, and colorectal cancers[49]. Proteomic profiling has shown promise in detecting pre-malignant conditions earlier than imaging or cytology, potentially allowing therapeutic intervention before disease progression[50].

Tumor Classification

Histopathological analysis, while foundational, is often subjective and lacks the precision needed for personalized treatment. Genomic and proteomic technologies provide objective molecular markers that can classify tumors based on their genetic and proteomic signatures. For example, microarray-based gene expression profiling has enabled the classification of breast cancer into molecular subtypes such as luminal A, luminal B, HER2-enriched, and basal-like, each with distinct clinical outcomes and treatment responses[51]. Proteomics contributes further by identifying protein expression levels and post-translational modifications, which cannot be captured through genomics alone. A well-known marker, BCL-2, is overexpressed in follicular lymphoma and aids in differentiating it from benign follicular hyperplasia[52]. Similarly, immunohistochemistry (IHC) and mass spectrometry-based proteomic profiling can stratify non-small cell lung carcinomas and lymphomas into subgroups with prognostic and therapeutic relevance[53].

Targeted Tumor Therapies and Tumor Metastasis

The most transformative impact of genomics and proteomics is in the area of targeted cancer therapies. These therapies focus on specific molecular abnormalities driving tumor growth. Imatinib targets the BCR-ABL fusion protein in chronic myeloid leukemia, trastuzumab targets HER2 in breast cancer, and gefitinib targets EGFR mutations in lung cancer[54]. Despite initial efficacy, many of these therapies face resistance, highlighting the need for real-time monitoring of proteomic changes to adapt treatments accordingly. The study of metastasis, which remains the primary cause of cancer mortality, has also benefited from proteogenomic approaches. Proteomics reveals the dynamic remodeling of signaling pathways and adhesion molecules during metastatic progression, while genomics provides insights into mutations associated with metastatic potential[55]. Together, these tools are being used to discover novel targets to inhibit metastatic spread and identify biomarkers for early metastatic events.

Application for Discovery of Protein Biomarkers

The identification of protein biomarkers has become a cornerstone of modern proteomic applications, especially in drug discovery and disease diagnosis. Biomarkers are indicators of biological states or conditions, and their detection provides vital information for diagnosing diseases, predicting therapeutic responses, and monitoring treatment efficacy. The advent of high-throughput proteomics, particularly mass spectrometry (MS)-based platforms, has transformed biomarker discovery by enabling the analysis of thousands of proteins simultaneously in complex biological samples such as plasma, urine, or tissue extracts[56]. Unlike genomics, proteomics does not require prior knowledge of target molecules, making it ideal for de novo discovery of disease-associated proteins. Critical to the success of biomarker discovery are the quality and reproducibility of sample preparation, robustness of proteomic platforms, and accuracy of bioinformatics analyses. Techniques such as liquid chromatography-tandem mass spectrometry (LC-MS/MS), capillary electrophoresis-mass spectrometry (CE-MS), and surface-enhanced laser desorption/ionization (SELDI) have significantly increased sensitivity and throughput, enabling researchers to detect low-abundance proteins that may serve as early indicators of disease[57]. Moreover, proteomics allows the study of post-translational modifications (PTMs) and protein-protein interactions, key functional elements often missed by transcriptomic approaches. Despite promising

findings, the clinical translation of candidate biomarkers remains limited by challenges in validation, regulatory approval, and standardization protocols[58].

Application in Renal Disease Diagnosis

Proteomics has shown tremendous promise in improving the diagnosis, prognosis, and treatment of renal diseases. Traditional markers like serum creatinine and albuminuria, although widely used, lack the sensitivity and specificity required for early disease detection. In contrast, proteomic profiling of urine and renal tissues has enabled the identification of disease-specific protein signatures that can potentially serve as early diagnostic and prognostic biomarkers[58, 59]. Urine is particularly attractive for proteomic studies due to its non-invasive collection and its direct reflection of kidney pathology. Using advanced proteomic tools such as two-dimensional gel electrophoresis, isoelectric focusing, and MS-based technologies, researchers have catalogued numerous proteins associated with specific renal conditions, including IgA nephropathy, membranous nephropathy, diabetic nephropathy, and lupus nephritis[60]. Additionally, proteomics aids in understanding the pathophysiology of acute kidney injury (AKI) and chronic kidney disease (CKD) by elucidating mechanisms of disease progression and identifying potential therapeutic targets[61]. Despite these advancements, clinical implementation is hindered by issues related to data reproducibility, standardized sample processing, and biomarker validation protocols.

Application in Autoantibody Profiling and Treatment of Autoimmune Diseases

Autoimmune diseases, characterized by aberrant immune responses against self-antigens, are often diagnosed based on clinical symptoms and limited serological tests. Proteomics offers an unbiased and systematic approach to profile autoantibodies and their corresponding autoantigens in patient samples. High-throughput techniques like protein microarrays and shotgun proteomics enable the identification of novel antigenic targets, thereby refining disease classification and potentially guiding personalized immunotherapy[62]. In diseases such as rheumatoid arthritis, systemic lupus erythematosus, multiple sclerosis, and type 1 diabetes, proteomic studies have been employed to detect disease-specific autoantibody profiles that differentiate between subtypes, track disease progression, and monitor treatment efficacy. These molecular signatures not only help in disease stratification but also shed light on epitope spreading, antibody isotype switching, and the dynamics of B-cell responses[63]. Furthermore, understanding the autoantibody repertoire through proteomics can reveal potential therapeutic targets for antigen-specific immunomodulation, offering a new frontier in the management of chronic autoimmune disorders.

Application in Cardiovascular Research

The integration of genomics and proteomics has significantly advanced our understanding of cardiovascular biology, disease mechanisms, and therapeutic strategies. Traditional genomic analyses have provided crucial insights into gene expression and mutations contributing to heart disease. However, the proteomic landscape adds a critical dimension by identifying post-translational modifications, protein–protein interactions, and dynamic protein expression in cardiovascular tissues under physiological and pathological conditions. Proteomics enables the identification of altered proteins and their modifications during conditions such as ischemia, hypertension, myocardial infarction, and heart failure. Technologies like two-dimensional electrophoresis (2-DE), liquid chromatography, and mass spectrometry (MS) have been instrumental in these studies[64]. By profiling the proteomes of diseased and healthy tissues, researchers can detect changes in protein expression and activity that cannot be inferred from genomic data alone[65].

Functional proteomics, focused on protein activity and signaling rather than just abundance, has been especially powerful in identifying mechanisms of cardiac hypertrophy and arrhythmogenesis. For instance, post-translational modifications such as phosphorylation and acetylation have been correlated with altered contractile function and energy metabolism in heart failure models[66]. Moreover, proteomic analysis has contributed to the discovery of novel biomarkers for early detection, risk stratification, and prognosis of cardiovascular diseases. Proteins identified in serum or cardiac tissue have shown potential as diagnostic tools, including those related to oxidative stress, inflammation, and myocardial injury [67].These discoveries not only improve diagnosis but also aid in the customization of treatments, key to the emerging field of precision cardiology[66]. In conclusion, proteomics complements genomics by bridging the gap between genotype and phenotype in cardiovascular disease. Its continued development will likely enhance both our mechanistic understanding and our clinical capabilities in managing heart disease.

Application in Nutrition Research

Genomics and proteomics are reshaping the field of nutritional science by enabling precise, molecular-level investigation of nutrient metabolism, dietary effects, and health outcomes. Genomic techniques allow the identification of gene variants associated with nutrient absorption, metabolism, and disease susceptibility, while proteomics enables researchers to examine how these genes are expressed and modulated by diet in real time. Proteomics provides a detailed profile of protein expression and modification in response to nutritional status, thereby facilitating the discovery of dietary biomarkers, the understanding of nutrient–gene interactions, and the development of personalized nutrition strategies[68]. Mass spectrometry and advanced separation techniques are used to assess dietary protein quality, absorption efficiency, and metabolic fate, particularly in complex biological samples such as blood and urine. Recent advances have shown that dietary factors such as polyphenols, fatty acids, and micronutrients significantly modulate the proteome, affecting processes like inflammation, oxidative stress, and insulin signaling[69]. Proteomics has also enabled high-resolution study of the intestinal epithelium, helping elucidate how various diets alter the gut barrier function and immune responses, key determinants of systemic health.

Furthermore, the proteomic approach supports the identification of early disease indicators and responders versus non-responders to specific dietary interventions, providing a scientific basis for individualized dietary planning[70]. In animal studies and human cohorts, proteomic tools have been applied to trace protein pathways involved in obesity, diabetes, aging, and cancer, improving our mechanistic understanding of nutrition-linked diseases. Proteomics, thus, not only enriches the understanding of nutrient dynamics at a molecular level but also offers practical applications in dietary assessment, disease prevention, and therapeutic nutrition. Its integration with genomic and metabolomic data promises a more comprehensive and personalized approach to nutritional health.

Conclusion

The integration of proteomic and genomic techniques has profoundly transformed the landscape of molecular biology, enabling deeper insight into the mechanisms of disease, enhancing diagnostic precision, and driving the development of targeted therapies. This review highlights the evolution and application of foundational techniques such as two-dimensional electrophoresis, mass spectrometry, Western blotting, and PCR, while also emphasizing their role in high-impact medical research areas, including oncology, nephrology, immunology, cardiology, and nutrition science. Genomic methods like PCR, recombinant DNA technology, and Southern blotting have enabled researchers to dissect genetic blue-

prints, identify mutations, and engineer precise genetic modifications. However, genomics alone cannot explain the dynamic behavior of proteins, the true functional molecules in the cell. This limitation underscores the essential role of proteomics in translating static genetic information into real-time biological function. Techniques such as mass spectrometry, ELISA, and protein microarrays allow for high-throughput protein identification, quantification, and functional analysis, making them indispensable in biomarker discovery and therapeutic development. In cancer research, proteogenomic tools enable earlier detection, refined tumor classification, and the creation of targeted treatments based on molecular profiles. In renal disease and autoimmune disorders, proteomics reveals disease-specific protein signatures that can inform diagnosis and monitor treatment response. Cardiovascular and nutrition research similarly benefits from proteomic insights into protein modifications, signaling pathways, and dietary influences on health outcomes. Ultimately, the convergence of genomics and proteomics offers a systems-level understanding of life, moving the field closer to the promise of precision medicine. While challenges such as low-abundance protein detection and data standardization remain, continued advances in analytical technologies and bioinformatics are rapidly overcoming these barriers. Together, these molecular tools provide a powerful platform for improving disease prevention, diagnosis, and therapy, paving the way for a more personalized and effective approach to human health.

References

1. Duan, D.D., 2010. Proteomics and Functional Proteomics. In Textbook of Pulmonary Vascular Disease. pp. 591-612. Boston, MA: Springer US.
2. Hondermarck, H., 2003. Breast cancer: when proteomics challenges biological complexity. Molecular & Cellular Proteomics, 2(5), pp.281-291.
3. Celis, J.E., Østergaard, M., Jensen, N.A., Gromova, I., Rasmussen, H.H. and Gromov, P., 1998. Human and mouse proteomic databases: novel resources in the protein universe. FEBS letters, 430 (1-2), pp.64-72.
4. Gevaert, K. and Vandekerckhove, J., 2001. Protein characterization: Analytical approaches and applications to proteomics. e LS.
5. Nagaraj, N., 2010. Developing mass spectrometry towards applications in clinical proteomics (Doctoral dissertation, Ludwig-Maximilians-Universität München).
6. Chow, M. et al. (2010) 'Proteomics and Mass Spectrometry Applications in Biomedical Research', Journal of biomolecular techniques. 12: 234-54
7. Kamal, A.H.M., Choi, J.S., Cho, Y.G., Kim, H.S., Song, B.H., Lee, C.W. and Woo, S.H., 2010. Comprehensive proteome analysis using quantitative proteomic technologies. Journal of Plant Biotechnology, 37(2), pp.196-204.
8. Graves, P.R. and Haystead, T.A., 2003. A functional proteomics approach to signal transduction. Recent Progress in Hormone Research, 58, pp.1-24.
9. Pattini, L., Bertacco, R., Candiani, G., Masseroli, M. and Servi, S., 2011. Trends in biomedical engineering: focus on Genomics and Proteomics. Journal of Applied Biomaterials and Biomechanics, 9(2), pp.98-108.
10. Van Regenmortel, M.H., 2001. Proteomics versus genomics. What type of structure–function relationship are we looking for?. Journal of Molecular Recognition, 14(6), pp.321-322.
11. Anderson, N.L. and Anderson, N.G., 1998. Proteome and proteomics: new technologies, new con-

cepts, and new words. Electrophoresis, 19(11), pp.1853-1861.

12. Lepilkina, O.V. and Grigorieva, A.I., 2025. Proteomic methods for separation and identification of milk proteins. Food systems, 7(4), pp.560-567.
13. Saikusa, K., Kinumi, T. and Kato, M., 2022. Development of native mass spectrometry with nano-electrospray ionization coupled to size exclusion chromatography for proteins. Rapid Communications in Mass Spectrometry, 36(21), p.e9395.
14. Ehkirch, A., Hernandez-Alba, O., Colas, O., Beck, A., Guillarme, D. and Cianférani, S., 2018. Hyphenation of size exclusion chromatography to native ion mobility mass spectrometry for the analytical characterization of therapeutic antibodies and related products. Journal of Chromatography B, 1086, pp.176-183.
15. Tubbs, C.E., 2000. The biochemical characterization of protein DE and its interaction with rat epididymal sperm. North Carolina State University.
16. Lecchi, P., Gupte, A.R., Perez, R.E., Stockert, L.V. and Abramson, F.P., 2003. Size-exclusion chromatography in multidimensional separation schemes for proteome analysis. Journal of biochemical and biophysical methods, 56(1-3), pp.141-152.
17. Ventouri, I.K., Veelders, S., Passamonti, M., Endres, P., Roemling, R., Schoenmakers, P.J., Somsen, G.W., Haselberg, R. and Gargano, A.F., 2023. Micro-flow size-exclusion chromatography for enhanced native mass spectrometry of proteins and protein complexes. Analytica Chimica Acta, 1266, p.341324.
18. Nadler, T.K., Wagenfeld, B.G., Huang, Y., Lotti, R.J., Parker, K.C. and Vella, G.J., 2004. Electronic Western blot of matrix-assisted laser desorption/ionization mass spectrometric-identified polypeptides from parallel processed gel-separated proteins. Analytical biochemistry, 332(2), pp.337-348.
19. Schroeder, W.A., 1972. [24] Degradation of peptides by the Edman method with direct identification of the phenylthiohydantoin-amino acid. In Methods in Enzymology (Vol. 25, pp. 298-313). Academic Press.
20. Chen, W., Yin, X., Mu, J. and Yin, Y., 2007. Subfemtomole-level protein sequencing by Edman degradation carried out in a microfluidic chip. Chemical Communications, (24), pp.2488-2490.
21. Smith, H., 2001. Brucella periplasmic protein sequencing by Edman degradation. Journal of Bacteriology, 183(4), pp.1272–1279.
22. Sutandy, F.X.R., et al., 2014. Protein microarrays: development and applications. Proteomics. 14 (13–14), pp.1486–1499.
23. Zhu, H., Klemic, J.F., Chang, S., Bertone, P., Casamayor, A., Klemic, K.G., Smith, D., Gerstein, M., Reed, M.A. and Snyder, M., 2000. Analysis of yeast protein kinases using protein chips. Nature Genetics, 26(3), pp.283-289.
24. Popescu SC, Snyder M, Dinesh-Kumar S, 2007. Arabidopsis protein microarrays for the high-throughput identification of protein-protein interactions. Plant Signal Behav. 2(5):416-20
25. Dunn, M.J., 1996. Electroblotting of proteins from polyacrylamide gels. Protein Purification Protocols, pp.363-370.
26. Kumar, A., et al., 2014. Diagnostic differentiation of Mycoplasma species using SDS-PAGE. Veterinary Research Communications. 38(1), pp.9–17.

27. Smyth, M. S., and Martin, J. H. 2000. X-ray crystallography. Molecular Pathology. 53(1), 8–14.
28. Lequin, R.M., 2005. Enzyme immunoassay (EIA)/enzyme-linked immunosorbent assay (ELISA). Clinical chemistry, 51(12), pp.2415-2418.
29. Eda, S., et al., 2006. Development of ELISA for MAP surface antigen detection. Journal of Immunological Methods. 315(1–2), pp.103–112.
30. Mullis, K.B., 1990. The unusual origin of the polymerase chain reaction. Scientific American. 262 (4), pp.56-65.
31. Manca, V. and Franco, G., 2008. Computing by polymerase chain reaction. Mathematical Biosciences, 211(2), pp.282-298.
32. Nicholl, D.S., 2023. An introduction to genetic engineering. Cambridge University Press.
33. Shafikhani, S., 2002. Factors affecting PCR-mediated recombination. Environmental microbiology, 4(8), pp.482-486.
34. Farooqui, A.K., Ahmad, H., Rehmani, M.U. and Husain, A., 2023. Quick and easy method for extraction and purification of Pfu-Sso7d, a high processivity DNA polymerase. Protein Expression and Purification, 208, p.106276.
35. Pal, A. and Pal, A., 2022. Recombinant DNA Technology. Protocols in Advanced Genomics and Allied Techniques, pp.31-47.
36. Jones, D.H. and Winistorfer, S.C., 1993. Use of polymerase chain reaction for making recombinant constructs. PCR Protocols: Current Methods and Applications, pp.241-250.
37. Bradley, R.D. and Hillis, D.M., 1997. Recombinant DNA sequences generated by PCR amplification. Molecular biology and evolution, 14(5), pp.592-593.
38. Jones, D.H. and Howard, B.H., 1991. A rapid method for recombination and site-specific mutagenesis by placing homologous ends on DNA using polymerase chain reaction. Biotechniques, 10(1), pp.62-66.
39. Allison, L.A., 2021. Fundamental molecular biology. John Wiley & Sons.
40. Sambrook, J. and Russell, D.W., 2001. Detection of DNA in agarose gels. Molecular Cloning, A Laboratory Manual, (3rd Ed.) Cold Spring Harbor Laboratory Press, New York, pp.5-14.
41. Guttmacher, A.E. and Collins, F.S., 2003. Welcome to the genomic era. New England Journal of Medicine, 349(10), pp.996-998.
42. Herschleb, J., Ananiev, G. and Schwartz, D.C., 2007. Pulsed-field gel electrophoresis. Nature protocols, 2(3), pp.677-684.
43. Southern, E.M., 1975. Detection of specific sequences among DNA fragments separated by gel electrophoresis. Journal of Molecular Biology. 98(3), pp.503-517.
44. Kurien, B.T. and Scofield, R.H. (2006). Western blotting. Methods. 38(4), pp.283–293.
45. Collins, F.S., Green, E.D., and Guttmacher, A.E. 2003. A vision for the future of genomics research. Nature. 422(6934): 835–847.
46. Brown, T.A., 2002. The human genome. In Genomes. 2nd edition. Wiley-Liss.
47. Parikh, A., Johnson, J. C., and Merchant, N. 2008. Genomics and proteomics in predicting cancer outcomes. Surgical Oncology Clinics of North America. 17(2), pp. 257–277.

48. Posadas, E.M., Gulley, J.L., Arlen, P.M., Trout, A., Parnes, H.L., Wright, J., Lee, M.J., Chung, E.J., Trepel, J.B., Sparreboom, A., and Chen, C., 2005. A phase II study of perifosine in androgen-independent prostate cancer. Cancer biology & therapy, 4(10), pp.1133-1137.
49. Meani, F., Pecorelli, S., Liotta, L. and Petricoin, E.F., 2009. Clinical application of proteomics in ovarian cancer prevention and treatment. Molecular diagnosis & therapy, 13, pp.297-311.
50. Hu, W., Wu, W., Kobayashi, R. and Kavanagh, J.J., 2004. Proteomics in cancer screening and management in gynecologic cancer. Current oncology reports, 6, pp.456-462.
51. Wu, W., Hu, W. and Kavanagh, J.J., 2002. Proteomics in cancer research. International Journal of Gynecological Cancer, 12(5), pp.409-423.
52. Baron, B., 2016. Application of proteomics to cancer therapy. Centre for Molecular Medicine and Biobanking, University of Malta.
53. Meyerson, M. and Carbone, D., 2005. Genomic and proteomic profiling of lung cancers: lung cancer classification in the age of targeted therapy. Journal of clinical oncology, 23(14), pp.3219-3226.
54. Pierobon, M., Wulfkuhle, J., Liotta, L.A. and Petricoin III, E.F., 2019. Utilization of proteomic technologies for precision oncology applications. Precision Medicine in Cancer Therapy, pp.171-187.
55. Mani, D.R., Krug, K., Zhang, B., Satpathy, S., Clauser, K.R., Ding, L., Ellis, M., Gillette, M.A., and Carr, S.A., 2022. Cancer proteogenomics: current impact and future prospects. Nature Reviews Cancer, 22(5), pp.298-313.
56. Konvalinka, A., Scholey, J.W. and Diamandis, E.P., 2012. Searching for new biomarkers of renal diseases through proteomics. Clinical chemistry, 58(2), pp.353-365.
57. Mischak, H., Delles, C., Vlahou, A. and Vanholder, R., 2015. Proteomic biomarkers in kidney disease: issues in development and implementation. Nature Reviews Nephrology, 11(4), pp.221-232.
58. Smith, M.P.W., Banks, R.E., Wood, S.L., Lewington, A.J. and Selby, P.J., 2009. Application of proteomic analysis to the study of renal diseases. Nature Reviews Nephrology, 5(12), pp.701-712.
59. Chen, L., Su, W., Chen, H., Chen, D.Q., Wang, M., Guo, Y. and Zhao, Y.Y., 2018. Proteomics for biomarker identification and clinical application in kidney disease. Advances in clinical chemistry, 85, pp.91-113.
60. Lv, Y. and Xie, Y. 2017. Application of proteomics in kidney disease research. Chinese Medical Journal. 6: 54–57.
61. Thongboonkerd, V., 2005. Proteomic analysis of renal diseases: unraveling the pathophysiology and biomarker discovery. Expert Review of Proteomics, 2(3), pp.349-366.
62. Rovin, B.H. and Klein, J.B., 2015. Proteomics and autoimmune kidney disease. Clinical immunology, 161(1), pp.23-30.
63. Wu, J., Chen, Y.D. and Gu, W., 2010. Urinary proteomics as a novel tool for biomarker discovery in kidney diseases. Journal of Zhejiang University Science B, 11(4), pp.227-237.
64. Wang, X.L., Fu, A., Spiro, C. and Lee, H.C., 2008. Clinical application of proteomics approaches in vascular diseases. PROTEOMICS–Clinical Applications, 2(2), pp.238-250.

65. Macri, J., and Rapundalo, S. T. 2001. Application of proteomics to the study of cardiovascular biology. Trends in cardiovascular medicine. 11(2), 66–75.

66. Arrell, D.K., Neverova, I. and Van Eyk, J.E., 2001. Cardiovascular proteomics: evolution and potential. Circulation research, 88(8), pp.763-773.

67. Matt, P., Carrel, T., White, M., Lefkovits, I. and Van Eyk, J., 2007. Proteomics in cardiovascular surgery. The Journal of Thoracic and Cardiovascular Surgery, 133(1), pp.210-214.

68. Wang, J., Li, D., Dangott, L.J. and Wu, G., 2006. Proteomics and its role in nutrition research. The Journal of nutrition, 136(7), pp.1759-1762.

69. Kussmann, M. and Affolter, M., 2006. Proteomic methods in nutrition. Current Opinion in Clinical Nutrition & Metabolic Care, 9(5), pp.575-583.

70. Kim, Y. S. and Milner, J. A., 2003. Nutritional Genomics and Proteomics in Cancer Prevention. Journal of Nutrition. 133(7): 2399–2504.