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METABOLISM IN MOTION: A COMPREHENSIVE REVIEW OF BIOCHEMICAL PROCESSES

Dr.R.R.Kumar[a], Thirugnanasambandam Ramanathan[b] , Dr.Saranya Arumugam[c], Dr. Amit Kumar Dutta[d]

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Abstract

Metabolism is a fundamental biological process that encompasses a complex network of biochemical reactions and pathways within cells. This comprehensive review explores the intricate mechanisms underlying metabolism, highlighting key biochemical processes involved in energy production, biosynthesis, and cellular homeostasis. From carbohydrate metabolism and lipid metabolism to protein metabolism and nucleotide metabolism, the review examines the interconnectedness of these processes and their regulation. Furthermore, it delves into the importance of metabolic pathways in health and disease, including metabolic disorders and cancer. The review also discusses emerging research areas such as metabolomics and metabolic engineering, shedding light on their potential applications in personalized medicine and biofuel production. By unravelling the dynamics of metabolism, we can gain insights into cellular function and pave the way for future advancements in various fields, including medicine, biotechnology, and drug discovery.

Keywords: *Metabolism, Biochemical processes, Energy production, Biosynthesis, Cellular homeostasis, Carbohydrate Metabolism, Lipid metabolism, Protein metabolism, Nucleotide metabolism, Regulation, metabolic disorders, Cancer, Metabolomics, Metabolic engineering, Personalized medicine, Biofuels.*

[a]Assistant Professor, Department of Biochemistry, Aarupadai Veedu Medical College and Hospital, Vinayaka Missions Research Foundation, Puducherry
[b]Associate Professor, Centre of Advanced Study in Marine Biology, Faculty of Marine Sciences, Annamalai University, Parangipettai -608502, Tamil Nadu, India.
[c]Teaching Assistant, Department of biomedical sciences, Alagappa University, Karaikudi, Tamilnadu
[d]Asst. Director,Amity Institute of Biotechnology,Amity University Jharkhand, Ranchi.

Corresponding Author: kumar.rangarajalu@avmc.edu.in

Co Author: drtrcasmb@gmail.com, drarsaranya@gmail.com, drakdutta81@gmail.com

I.INTRODUCTION

Metabolism is a fundamental biological process that lies at the core of cellular function, enabling organisms to acquire and utilize energy, synthesize molecules, and maintain cellular homeostasis. It encompasses a complex network of biochemical reactions and pathways that occur within cells. Understanding the intricate biochemical processes involved in metabolism is of paramount importance. These processes govern energy production, biosynthesis of essential molecules, and the regulation of cellular functions. Disruptions or dysregulation in metabolism can lead to various diseases and disorders, making it crucial to unravel the underlying mechanisms [1].

The purpose of this comprehensive review is to delve into the multifaceted world of metabolism and provide a detailed exploration of its biochemical processes. By examining the interconnectedness of these processes, we aim to shed light on the fundamental principles that govern metabolism and the implications for cellular function. The scope of this review encompasses key aspects of metabolism, including carbohydrate metabolism, lipid metabolism, protein metabolism, and nucleotide metabolism. These processes are interlinked and tightly regulated to maintain energy balance, supply building blocks for cellular structures, and support essential cellular functions.

By elucidating the intricacies of metabolism, we can gain valuable insights into its role in health and disease. The review will touch upon the importance of metabolic pathways in various conditions, including metabolic disorders and cancer, highlighting the significance of understanding these processes for diagnosing, treating, and preventing diseases. Furthermore, this review will discuss emerging research areas such as metabolomics and metabolic engineering. These fields offer new avenues for studying metabolism and its potential applications in personalized medicine, biomarker discovery, and biofuel production. By providing a comprehensive overview of biochemical processes in metabolism, this review aims to contribute to the collective knowledge of cellular metabolism and inspire further research and advancements in medicine, biotechnology, and drug discovery[2].

II. CARBOHYDRATE METABOLISM

Carbohydrate metabolism is a central aspect of cellular energy production and plays a crucial role in maintaining energy balance within the body. It involves the breakdown, synthesis, and regulation of glucose and other carbohydrates. The key processes involved in carbohydrate metabolism are:

Glycolysis

Glycolysis is the initial step in carbohydrate metabolism and occurs in the cytoplasm of cells. It involves the breakdown of glucose into pyruvate through a series of enzymatic reactions. Along with the generation of ATP, glycolysis produces intermediates that are essential for other metabolic pathways [3].

Citric Acid Cycle (TCA cycle)

Also known as the Krebs cycle or the tricarboxylic acid cycle, the TCA cycle takes place in the mitochondria. It further breaks down pyruvate and generates ATP, NADH, and $FADH_2$. Additionally, the TCA cycle provides precursor metabolites for other metabolic pathways, such as amino acid synthesis.

Glycogen Metabolism

Glycogen serves as a storage form of glucose in animals and humans. Glycogen metabolism involves the synthesis (glycogenesis) and breakdown (glycogenolysis) of glycogen. During periods of low glucose availability, glycogen is broken down to release glucose, maintaining blood glucose levels and providing energy for various tissues [4].

Gluconeogenesis

Gluconeogenesis is the process by which glucose is synthesized from non-carbohydrate precursors, such as amino acids, lactate, and glycerol. It occurs mainly in the liver and kidneys and is crucial for providing glucose during prolonged fasting or low carbohydrate intake.These processes in carbohydrate metabolism are tightly regulated to ensure a constant supply of energy and maintain glucose homeostasis in the body. The balance between glycolysis and gluconeogenesis is particularly important in maintaining blood glucose levels and providing energy to different tissues based on metabolic demands. Understanding the intricacies of carbohydrate metabolism is essential in various fields, including nutrition, metabolism-related disorders such as diabetes, and metabolic engineering for biofuel production. The regulation of these processes and their dysregulation in disease states continue to be active areas of research and therapeutic intervention [5].

III. LIPID METABOLISM

Lipid metabolism is a complex set of processes that regulate the synthesis, breakdown, and utilization of lipids, which include fatty acids, triglycerides, and cholesterol. Lipids serve as essential components of cell membranes, energy storage molecules, and signalling molecules. The key processes involved in lipid metabolism are:

Lipogenesis

Lipogenesis refers to the synthesis of fatty acids and triglycerides. It occurs primarily in the liver and adipose tissue. Lipogenesis involves the conversion of excess glucose or dietary carbohydrates into fatty acids through a series of enzymatic reactions. These fatty acids are then esterified to glycerol, forming triglycerides, which are stored as energy reserves in adipocytes [6].

Beta-oxidation

Beta-oxidation is the process by which fatty acids are broken down to produce ATP and acetyl-CoA. It takes place primarily in the mitochondria. Fatty acids are sequentially oxidized by a series of enzymatic reactions, leading to the release of acetyl-CoA, NADH, and $FADH_2$. Acetyl-CoA enters the citric acid cycle for further energy production.

Lipolysis

Lipolysis is the breakdown of stored triglycerides into fatty acids and glycerol for energy utilization. Hormone-sensitive lipase and adipose triglyceride lipase are key enzymes involved in lipolysis. During periods of energy demand, lipolysis is stimulated, allowing the release of fatty acids from adipose tissue for energy production in various tissues [7].

Cholesterol Metabolism

Cholesterol metabolism involves the synthesis, transport, and regulation of cholesterol levels in the body. Cholesterol is a vital component of cell membranes and serves as a precursor for the synthesis of hormones, bile acids, and vitamin D. It is synthesized primarily in the liver, and its levels are tightly regulated through feedback mechanisms. Cholesterol is transported in the bloodstream by lipoproteins, including LDL (low-density lipoprotein) and HDL (high-density lipoprotein).

Understanding lipid metabolism is crucial in various contexts, such as nutrition, obesity, cardiovascular diseases, and metabolic disorders. Dysregulation of lipid metabolism can lead to conditions like dyslipidemia, fatty liver disease, and atherosclerosis. Moreover, lipid metabolism plays a significant role in energy homeostasis, and disturbances in this process can contribute to metabolic disorders [8].

Research in lipid metabolism focuses on unravelling the molecular mechanisms involved, identifying potential therapeutic targets, and exploring the links between lipid metabolism and various diseases. Additionally, lipid metabolic engineering has implications in areas such as biofuel production, where optimizing lipid synthesis in microorganisms can enhance biofuel yield and sustainability.

IV. PROTEIN METABOLISM

Protein metabolism encompasses the complex processes involved in the synthesis, degradation, and utilization of proteins within cells. Proteins are essential macromolecules that perform various functions in the body, including enzymatic activity, structural support, transport, and signaling. The key processes involved in protein metabolism are:

Protein Synthesis

Protein synthesis involves the transcription of DNA to messenger RNA (mRNA) and the subsequent translation of mRNA into a polypeptide chain. This process occurs in the cytoplasm and involves ribosomes, transfer RNA (tRNA), and various protein factors. Post-translational modifications, such as folding, cleavage, and addition of chemical groups, further refine the structure and function of proteins [9].

Protein Degradation

Protein degradation is essential for maintaining protein homeostasis and removing damaged or unnecessary proteins. The two major pathways involved in protein degradation are the ubiquitin-proteasome system and autophagy. In the ubiquitin-proteasome system, proteins are targeted for degradation by the attachment of ubiquitin molecules, marking them for recognition and subsequent proteasomal degradation. Autophagy involves the sequestration of proteins and organelles into autophagosomes, which fuse with lysosomes for degradation and recycling of their components [10].

Amino Acid Metabolism

Amino acid metabolism encompasses the interconversion and utilization of amino acids for energy production and biosynthesis. Amino acids can be used as building blocks for protein synthesis or can be metabolized to generate ATP through various pathways. For example, amino acids can enter the citric acid cycle as intermediates or be converted to glucose via gluconeogenesis. Some amino acids also serve as precursors for the synthesis of important biomolecules, such as neurotransmitters, nucleotides, and heme [11].

Understanding protein metabolism is crucial for various areas of research and medicine. It plays a significant role in understanding the mechanisms of genetic diseases, protein folding disorders, and the development of targeted therapies. Protein metabolism is also of interest in the field of sports nutrition, where optimizing protein synthesis and degradation pathways can enhance muscle growth and recovery.

Research in protein metabolism aims to unravel the intricacies of protein synthesis, degradation, and amino acid metabolism. This includes investigating the regulation of protein turnover, identifying factors involved in protein quality control, and exploring the role of amino acids in cellular signalling and metabolism [12].

By gaining a comprehensive understanding of protein metabolism, researchers can shed light on the molecular mechanisms underlying cellular function, disease processes, and potential therapeutic interventions.

V. NUCLEOTIDE METABOLISM

Nucleotide metabolism encompasses the processes involved in the synthesis, degradation, and recycling of nucleotides, which are the building blocks of DNA and RNA. Nucleotides play essential roles in cellular processes, including DNA replication, RNA synthesis, energy transfer, and cell signaling. The key processes involved in nucleotide metabolism are:

Purine Biosynthesis

Purine biosynthesis is the de novo synthesis of purine nucleotides, including adenine and guanine. This pathway involves a series of enzymatic reactions that convert simple precursors, such as amino acids and carbon dioxide, into purine nucleotides. The end product of purine biosynthesis is inosine monophosphate (IMP), which serves as a precursor for the synthesis of ATP, GTP, and other important purine nucleotides [13].

Pyrimidine Biosynthesis

Pyrimidine biosynthesis is the de novo synthesis of pyrimidine nucleotides, such as cytosine, thymine, and uracil. The pathway begins with the formation of carbamoyl phosphate and progresses through several enzymatic steps to produce uridine monophosphate (UMP), which serves as a precursor for the synthesis of other pyrimidine nucleotides.

Nucleotide Salvage Pathways

Nucleotide salvage pathways are responsible for the recycling of nucleotide bases derived from the degradation of DNA and RNA. In these pathways, the nucleotide bases released during DNA and RNA turnover are salvaged and converted back into nucleotides. This process conserves energy and resources by reusing the bases instead of de novo synthesis.

Understanding nucleotide metabolism is crucial for various areas of research, including genetics, molecular biology, and drug development. Dysregulation of nucleotide metabolism can lead to genetic disorders, cancer, and other diseases. Targeting nucleotide metabolism pathways has also been a strategy in the development of chemotherapeutic agents [14].

Research in nucleotide metabolism focuses on elucidating the enzymatic reactions and regulatory mechanisms involved in purine and pyrimidine biosynthesis. This includes studying the role of specific enzymes, investigating the regulation of nucleotide synthesis in response to cellular needs, and exploring the impact of nucleotide metabolism dysregulation on cellular processes.

By unraveling the intricacies of nucleotide metabolism, researchers can gain insights into the molecular mechanisms underlying DNA and RNA synthesis, energy metabolism, and cellular signaling. Furthermore, understanding nucleotide metabolism provides opportunities for the development of therapeutic interventions and the design of novel drugs targeting nucleotide synthesis or salvage pathways [15].

VI. REGULATION OF METABOLIC PATHWAYS

Metabolic pathways are tightly regulated to maintain energy homeostasis and respond to changing physiological conditions. Regulation occurs at various levels, including hormonal regulation, allosteric regulation, and signal transduction pathways. These mechanisms ensure that metabolic processes are coordinated and adapted to meet the energy and biosynthetic needs of the organism. The key regulatory mechanisms involved in metabolic pathways are:

Hormonal Regulation

Hormones, such as insulin, glucagon, and other hormones, play a crucial role in metabolic control. Insulin is released in response to high blood glucose levels and promotes glucose uptake by cells, stimulates glycogen synthesis, and inhibits gluconeogenesis. Glucagon, released during low blood glucose levels, stimulates glycogen breakdown and gluconeogenesis. Other hormones, such as adrenaline, cortisol, and growth hormone, also contribute to metabolic regulation by modulating various metabolic processes in response to different physiological states [16].

Allosteric Regulation

Allosteric regulation involves the modulation of enzyme activity by small molecules that bind to regulatory sites distinct from the active site. Allosteric regulators can activate or inhibit enzyme activity, thereby controlling the flux of metabolic reactions. For example, ATP acts as a negative allosteric regulator of phosphofructokinase, a key enzyme in glycolysis, to prevent unnecessary ATP consumption when energy levels are sufficient. Allosteric regulation allows metabolic pathways to respond rapidly to changes in substrate availability, product levels, or energy status [17].

Signal Transduction Pathways

Signal transduction pathways play a crucial role in integrating cellular signals and coordinating metabolic responses. Signalling molecules, such as hormones, growth factors, and neurotransmitters, bind to specific receptors on the cell surface or within the cell, initiating intracellular signalling cascades. These cascades involve protein kinases, phosphorylation events, and transcription factors that ultimately regulate gene expression and enzyme activity. For example, the activation of AMP-activated protein kinase (AMPK) in response to low energy levels leads to the up regulation of energy-producing pathways and the down regulation of energy-consuming processes.

Understanding the regulation of metabolic pathways is essential for comprehending how cells maintain energy balance, adapt to changing nutrient availability, and respond to physiological signals. Dysregulation of metabolic regulation can lead to metabolic disorders, obesity, diabetes, and other diseases.

Research in the field of metabolic regulation focuses on uncovering the signalling pathways, transcriptional regulators, and post-translational modifications involved in metabolic control. This includes studying the cross-talk between signalling pathways, identifying key regulatory molecules, and elucidating how dysregulation contributes to disease states.

By unraveling the regulatory mechanisms of metabolic pathways, researchers can gain insights into the complex interplay between metabolism and cellular signalling. This knowledge opens avenues for developing targeted interventions to modulate metabolic processes, improve metabolic health, and address metabolic disorders [18].

VII. METABOLIC PATHWAYS IN HEALTH AND DISEASE

Metabolic pathways play a critical role in maintaining health and are closely linked to various diseases. Understanding the alterations in metabolic pathways associated with disease states provides insights into disease mechanisms and potential therapeutic targets. Two significant areas where metabolic pathways are involved in health and disease are metabolic disorders and cancer metabolism.

Metabolic Disorders

Metabolic disorders encompass a range of conditions characterized by abnormalities in metabolic pathways. Common examples include diabetes, obesity, and inborn errors of metabolism. Diabetes mellitus, for instance, is characterized by impaired glucose metabolism due to insufficient insulin production or insulin resistance. Obesity involves dysregulation of lipid metabolism, leading to excessive fat accumulation. Inborn errors of metabolism result from genetic defects in specific enzymes or transporters, affecting the metabolism of carbohydrates, amino acids, or lipids. Understanding the underlying metabolic dysregulation in these disorders is crucial for developing effective treatments and management strategies.

Cancer Metabolism

Cancer cells exhibit distinct metabolic rewiring to support their rapid proliferation and survival. Alterations in metabolic pathways enable cancer cells to fulfill their increased energy demands and biosynthetic requirements. One prominent example is the Warburg effect, where cancer cells preferentially rely on glycolysis for energy production even in the presence of sufficient oxygen (aerobic glycolysis). This metabolic shift provides advantages for cancer cell growth and survival. Additionally, cancer cells exhibit changes in amino acid metabolism, lipid metabolism, and nucleotide metabolism to support their altered metabolic demands. Exploiting the metabolic vulnerabilities of cancer cells has emerged as an area of therapeutic investigation in oncology.

Understanding the metabolic pathways associated with these diseases has implications for diagnosis, treatment, and prevention. In metabolic disorders, identifying specific metabolic defects and developing targeted therapies can help restore metabolic balance and improve patient outcomes. In cancer metabolism, targeting altered metabolic pathways holds promise for developing novel therapeutic strategies and combination therapies to selectively target cancer cells.

Research in these areas involves studying the molecular mechanisms underlying metabolic dysregulation, identifying metabolic biomarkers, and developing interventions to modulate metabolic pathways. Advances in metabolomics, a field that explores the comprehensive analysis of metabolites in biological systems, have facilitated a deeper understanding of metabolic alterations in disease states.By elucidating the role of metabolic pathways in health and disease, researchers aim to develop personalized medicine approaches, discover novel therapeutic targets, and improve patient outcomes in metabolic disorders and cancer [19].

VIII. EMERGING RESEARCH AREAS

As our understanding of metabolism continues to expand, several emerging research areas have gained prominence. These areas focus on utilizing advanced technologies and approaches to explore metabolism in greater depth and harness its potential for various applications. Two significant emerging research areas are metabolomics and metabolic engineering.

Metabolomics

Metabolomics is a rapidly evolving field that involves the high-throughput analysis of metabolites in biological systems. It aims to provide a comprehensive snapshot of the metabolic profile and dynamics of an organism, tissue, or cell. Metabolomics enables the identification and quantification of a wide range of small molecules, including endogenous metabolites and metabolic by-products. By studying these metabolites, researchers can gain insights into metabolic phenotypes, identify biomarkers for disease diagnosis and prognosis, and understand the effects of environmental factors and therapeutic interventions on metabolism. Metabolomics has applications in diverse fields, including personalized medicine, nutritional science, toxicology, and drug discovery.

Metabolic Engineering

Metabolic engineering involves the manipulation of metabolic pathways in microorganisms, plants, or other systems to optimize desired outcomes. It combines principles from biology, genetics, and engineering to enhance the production of specific metabolites, such as pharmaceuticals, biofuels, or industrial chemicals. Metabolic engineers employ genetic and biochemical approaches to modify enzyme activities, redirect metabolic fluxes, and introduce novel metabolic pathways. By manipulating and fine-tuning metabolic networks, metabolic engineering aims to enhance yield, productivity, and sustainability in various biotechnological applications. This field has the potential to revolutionize industries such as pharmaceuticals, bioenergy, and agriculture, offering greener and more efficient production methods.

Both metabolomics and metabolic engineering are rapidly evolving fields that contribute to our understanding of metabolism and its applications. Metabolomics provides a comprehensive and dynamic view of metabolism, enabling researchers to uncover metabolic signatures, identify novel therapeutic targets, and develop personalized interventions. On the other hand, metabolic engineering harnesses the power of metabolic pathways to produce valuable compounds, optimize biofuel production, and engineer more sustainable industrial processes.

Continued advancements in technology, such as mass spectrometry, nuclear magnetic resonance (NMR) spectroscopy, and high-throughput omics approaches, will further drive innovation in metabolomics. Likewise, developments in genetic engineering, synthetic biology, and computational modelling will enhance the precision and capabilities of metabolic engineering.

Together, these emerging research areas hold great promise for unlocking the full potential of metabolism and its applications in medicine, biotechnology, and sustainable resource utilization. The integration of metabolomics and metabolic engineering will continue to push the boundaries of our understanding and enable the development of innovative solutions to address complex challenges in various fields [20].

IX. CONCLUSION

In conclusion, understanding the intricate biochemical processes in metabolism is of paramount importance. Metabolism serves as the foundation of cellular function, playing a vital role in energy production, biosynthesis, and cellular homeostasis.

Through this comprehensive review, we have explored the key biochemical processes involved in metabolism, including carbohydrate metabolism, lipid metabolism, protein metabolism, nucleotide metabolism, and their regulation. Throughout our exploration, we have recognized the interconnectedness of these metabolic pathways and their significance in maintaining health and preventing disease. We have seen how disruptions in these pathways can lead to metabolic disorders, obesity, diabetes, and cancer. By unravelling the dynamics of metabolism, researchers have made significant advancements in understanding the molecular mechanisms underlying these conditions.

The review has also highlighted emerging research areas, such as metabolomics and metabolic engineering, which hold great promise in the field of metabolism. Metabolomics allows for the high-throughput analysis of metabolites, leading to the discovery of metabolic phenotypes, identification of biomarkers, and personalized medicine approaches. On the other hand, metabolic engineering provides opportunities for manipulating metabolic pathways to optimize drug production, biofuel synthesis, and other biotechnological applications. Looking ahead, the potential applications of understanding metabolism are vast. In personalized medicine, a deeper understanding of metabolic processes can help in the development of tailored therapies and precision medicine approaches. In biotechnology, metabolic engineering can revolutionize the production of valuable compounds and contribute to the development of sustainable and eco-friendly processes. Additionally, the exploration of metabolic pathways holds promise for identifying novel drug targets and advancing drug discovery efforts.

As we continue to unravel the complexities of metabolism, future research should focus on elucidating the finer details of metabolic regulation, expanding our knowledge of metabolic interactions and networks, and applying advanced technologies to further our understanding. Furthermore, interdisciplinary collaborations between biochemists, geneticists, computational biologists, and clinicians will be crucial in harnessing the full potential of metabolism for the benefit of human health and the environment. In conclusion, the comprehensive understanding of biochemical processes in metabolism opens new horizons for research, innovation, and improved health outcomes. By harnessing the power of metabolism, we can pave the way for advancements in personalized medicine, biotechnology, and drug discovery, ultimately leading us to a healthier and more sustainable future.

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