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Message from the Principal

It is with profound joy that I present the first edition of *VERITAS – Edmundian Journal of Multidisciplinary Research (EJMR)*, a pioneering publication that embodies our institution's unwavering commitment to the pursuit of truth, academic excellence, and intellectual integrity. As our college's inaugural version of our e-journal, *VERITAS* marks a significant step toward expanding access to scholarly discourse through digital platforms, ensuring that research reaches a wider audience beyond the confines of traditional print.

The name *VERITAS*—a Latin word meaning "truth," "truthfulness," and "that which is true"—carries deep philosophical and moral significance. In Roman mythology, Veritas, the Goddess of Truth and daughter of Saturn, symbolizes purity and the unveiling of reality. Across intellectual history, *veritas* has been a guiding ideal in philosophy, theology, and academia; it is famously echoed in the biblical phrase "*Veritas vos liberabit*" ("The truth shall set you free") and continues to inspire scholarly traditions that seek wisdom grounded in honesty and reason. Thus, *veritas* transcends mere factual accuracy; it signifies moral virtue, honesty, and the alignment of human understanding with the true nature of things.

In this spirit, *VERITAS* serves as a vibrant scholarly platform that fosters multidisciplinary inquiry, critical thinking, and the relentless pursuit of knowledge across diverse fields. It reflects our conviction that truth emerges through dialogue, collaboration, and the integration of varied perspectives—an approach essential for addressing the complex challenges of our contemporary world.

I extend my sincere gratitude to the Journal Editorial Board for their meticulous dedication and scholarly rigor in bringing this publication to fruition. I also commend the Research & Publication Cell (RPC) for its continued efforts in strengthening our research culture and upholding academic standards.

I wish to place on record my special appreciation to Dr. Neeta Pathaw, Dr. Samrat Adhikari, and Mr. Sumit Deb, Director (IQAC), whose visionary leadership, steadfast commitment, and inspirational guidance have been instrumental in nurturing a dynamic research ecosystem at St. Edmund's College. Their efforts have empowered both faculty and students to engage meaningfully in scholarly discourse.

May *VERITAS* continue to illuminate the path toward truth, enrich the academic community, and contribute to the advancement of knowledge for the betterment of society.



Br. Sunil Britto
Principal (i/c)
St. Edmund's College, Shillong

Message from the Editor-in-chief

The launch of VERITAS – Edmundian Journal of Multidisciplinary Research (EJMR) marks an important chapter in the academic journey of St. Edmund's College. Recognizing the need for meaningful academic exchange, VERITAS has been conceived as a multidisciplinary platform that welcomes diverse perspectives and encourages conversations across disciplinary boundaries.

This inaugural issue, which embodies our shared aspiration to create a platform where young researchers both faculty and students can get recognition thereby serving as a catalyst for social and intellectual progress. Through the publication of original research and critical reflections, this journal seeks to promote an academic culture that values dialogue, innovation, and the responsible dissemination of knowledge.

The inaugural issue is the result of the dedication and perseverance of many individuals who have worked tirelessly to transform this vision into reality. I express my sincere appreciation to the contributors whose research enriches these pages and to the reviewers whose expertise and thoughtful evaluations have ensured the quality of the published work. My sincere gratitude also extends to the members of the Editorial Board, with a special mention to Dr. Neeta Pathaw, and the Research & Publication Cell for their unwavering commitment and professionalism throughout this endeavour.

I would like to acknowledge the constant encouragement and support extended by the leadership of St. Edmund's College and the Internal Quality Assurance Cell (IQAC), whose commitment to academic excellence has strengthened our institutional research environment. Their efforts have helped foster a community in which both faculty and students are inspired to pursue scholarly inquiry with enthusiasm and integrity.

As we present the first issue of VERITAS, we do so with the hope that it will become a vibrant forum for intellectual engagement and interdisciplinary collaboration. May this journal continue to inspire rigorous scholarship, stimulate meaningful dialogue, and contribute to the creation and dissemination of knowledge for the benefit of society.



Dr V. R. Rao
Editor-in-chief
VERITAS
St. Edmund's College, Shillong

Message from the Director, IQAC

It gives me immense pleasure to present the inaugural edition of **VERITAS – Edmundian Journal of Multidisciplinary Research (EJMR)**, an initiative of the Internal Quality Assurance Cell (IQAC), St. Edmund's College, Shillong. The launch of this journal marks a significant milestone in our institution's continuing commitment to fostering a vibrant culture of research, innovation, and academic excellence.

In today's rapidly evolving academic landscape, quality research and scholarly communication are indispensable for the advancement of knowledge and the holistic development of higher education institutions. VERITAS has been conceived as a multidisciplinary, peer-reviewed, and open-access platform that encourages students, research scholars, and faculty members to disseminate original research findings, critical reviews, case studies, and innovative ideas across the disciplines of Science, Technology, Arts, Humanities, and Commerce.

The establishment of this journal reflects IQAC's vision of integrating research with quality assurance by promoting ethical publication practices, interdisciplinary collaboration, and academic integrity. We believe that nurturing a research-oriented mindset among learners and educators will not only enhance institutional quality but also contribute meaningfully to society through evidence-based knowledge and innovative solutions.

I sincerely appreciate the dedicated efforts of the Editorial Board, reviewers, faculty members, researchers, and all contributors whose commitment and hard work have made the publication of this inaugural issue possible. Their collective endeavour demonstrates the spirit of academic collaboration that defines St. Edmund's College.

I am confident that VERITAS will evolve into a respected scholarly platform that inspires intellectual curiosity, encourages critical thinking, and showcases high-quality research from our institution and beyond. I invite researchers from diverse disciplines to contribute to future issues and become part of this growing academic community.

On behalf of the Internal Quality Assurance Cell, I extend my best wishes for the continued success of VERITAS and congratulate everyone associated with its first edition. May this journal serve as a beacon of knowledge, excellence, and truth, upholding the highest standards of scholarly publishing.



Mr Sumit Deb
Director, Internal Quality Assurance Cell (IQAC)
St. Edmund's College, Shillong

Reviewers' Profile

Prof (Dr) Arnab Sen, FIAAT, FLS, FNABS

Vice-Chancellor of Raiganj University, West Bengal, and former Professor of Botany at the University of North Bengal, Prof. Sen is a distinguished scholar in Botany, Biotechnology, Bioinformatics, and Nanobiotechnology. He earned his PhD from North-Eastern Hill University (NEHU), Shillong, and has coordinated the DBT Bioinformatics Facility Centre and the Biswa Bangla Genome Centre. His research spans nanotechnology, cytogenetics, metagenomics, drug design, network pharmacology, and plant sciences, with 26 doctoral scholars supervised to date. He has authored over 200 publications and received the DBT CREST Award, DBT Overseas Associateship, and DST Fast Track Young Scientist Award. He served as Principal Investigator of the U.S. Department of Energy's Frankia Genome Project and is a Fellow of the Linnean Society, London (FLS), the National Academy of Biological Sciences (FNABS), and the Indian Association of Angiosperm Taxonomy (FIAAT), with extensive experience as editor and reviewer for leading journals.

Prof (Dr) Dipak Sinha, FRSC, FNESA

Senior Professor of Chemistry in Nagaland University and currently serves as the Pro-Vice Chancellor of Nagaland University. An alumnus of St. Edmund's College, Shillong, he obtained his Ph.D. from North-Eastern Hill University (NEHU) and has been associated with Nagaland University since 1998. Over the years, he has made significant contributions to teaching, research, academic administration, and higher education policy implementation. His research interests include Environmental chemistry, Photocatalysis, Activated carbon-based materials, Graphene nanocomposites, and radiation studies. He has guided 12 Ph.D. scholars, published over 95 research papers in reputed journals, secured 8 granted patents, and successfully completed several externally funded research projects. Prof. Sinha was awarded the prestigious DST-BOYSCAST Fellowship, which enabled him to undertake postdoctoral research at the Hahn-Meitner Institute, Berlin, Germany in the year 2004. He is a Fellow of the Royal Society of Chemistry (FRSC) and the National Environmental Science Academy (FNESA), and was selected for the Fulbright-Nehru International Education Administrators Award (2025–26). As Nodal Officer for NEP-2020 and former Director of IQAC, he has played a key role in curriculum reforms, quality assurance, and institutional development at Nagaland University. His contributions have earned him recognition as a respected academic leader, researcher, and higher education administrator from Northeast India.

Prof (Dr) Kushal Kalita

Professor in the Department of Physics at Gauhati University, Prof. Kalita earned his M.Sc. and Ph.D. from the University of Delhi and completed postdoctoral research at the Australian National University, Canberra. A specialist in experimental and theoretical nuclear physics, his work addresses nuclear reaction dynamics, heavy-ion-induced reactions, sub-barrier fusion, radioactive ion beams, and detector development, advancing the understanding of fusion mechanisms and multi-nucleon transfer processes. He has collaborated with the Inter-University Accelerator Centre (IUAC), Bhabha Atomic Research Centre (BARC), and FAIR-PANDA, Germany, and has published over 80 papers with more than 800 citations. He has supervised several doctoral scholars and holds leadership roles in the Physics Academy of North East (PANE), the Assam Physical Society, and the Gauhati University Teachers' Association.

Dr Suktilang Majaw

Associate Professor in the Department of Biotechnology and Bioinformatics, and Director of the Design Innovation Centre (DIC) at North-Eastern Hill University (NEHU), Shillong, Dr. Majaw holds an M.Sc. in Biotechnology from Tezpur University and a Ph.D. in Biochemistry from NEHU. Her research centres on biochemistry, immunology, medicinal plants, metabolic disorders, diabetes, oxidative stress, cancer biochemistry, and natural product-based therapeutics, with particular

focus on the antidiabetic, antioxidant, and anti-inflammatory properties of medicinal plants indigenous to Northeast India. She has authored numerous research articles, book chapters, and reviews, and has served as Guest Editor of The NEHU Journal, alongside active involvement in interdisciplinary research, mentoring, and scholarly review.

Dr Indranil Das

Assistant Professor in the Department of Microbiology and Biotechnology, School of Health Science and Translational Research, Techno India University, Tripura, Dr. Das holds a B.Sc. in Biotechnology from Karimganj College, an M.Sc. from Utkal University, and an M.Phil./Ph.D. in Life Science and Bioinformatics from Assam University, Silchar. His doctoral research examined the toxicological effects of pyrethroid pesticides on amphibian populations through molecular, biochemical, and computational approaches. His research interests include environmental toxicology, molecular genetics, amphibian ecology, bioinformatics, and ecological risk assessment, with several publications in national and international journals and active participation in scientific conferences and academic forums.

Dr Malabika Biswas

Professor in the Department of Biological Sciences at BITS Pilani, K. K. Birla Goa Campus, Dr. Biswas earned her Ph.D. in Biochemistry and Molecular Biology from Bose Institute, Kolkata (2008), studying the Repressor and Cro proteins of *Staphylococcus aureus* phage $\Phi 11$, following an M.Sc. in Biotechnology from Calcutta University and a B.Sc. (Honours) in Biochemistry from St. Edmund's College, NEHU, Shillong. Her research on the molecular biology and gene-regulatory elements of bacteriophage $\Phi 11$, and on human–staphylococcal protein interactions, has advanced the development of regulated phage-derived vectors and novel therapeutic strategies against multi-drug-resistant *S. aureus*. She has authored 27 peer-reviewed publications—including cover-featured papers in FEBS Letters and the Journal of Biochemistry—and holds a filed patent for a bacteriophage lytic-protein identification system. As Principal Investigator, she has led major funded projects including a DST-CRG grant (₹40 lakhs) and an ongoing DHR project (₹30 lakhs), and has mentored numerous doctoral and postdoctoral scholars. A recipient of the MBSI Excellence in Research Award (2025) and Best Oral Presenter honours (2024, 2025), she is a frequent invited speaker at national and international conferences, holds life membership in several professional societies, and has served as Convenor of multiple international conferences while contributing to key institutional committees at BITS Pilani.

Dr Jibitesh Dutta

Associate Professor in the Mathematics Division, Department of Basic Sciences and Social Sciences, North-Eastern Hill University (NEHU), Shillong, Dr. Dutta brings over twenty-five years of experience in mathematical cosmology, gravitation, and applied mathematics. His research addresses modified gravity theories, dynamical systems methods in cosmology, cosmological perturbation theory, dark energy models, and spectral graph theory, with notable contributions to alternative theories of gravity, cosmic acceleration, structure formation, and the qualitative analysis of cosmological models. He has authored more than 35 peer-reviewed publications in reputed international journals, supervised multiple Ph.D. scholars, and served as Principal Investigator of a SERB-DST funded project on cosmological perturbations in modified gravity. His honours include the India Top Cited Paper Award (2021, Institute of Physics), the Erasmus+ Fellowship, the Young Relativist Award, and an M.Sc. Gold Medal, alongside consecutive terms as Visiting Associate at the Inter-University Centre for Astronomy and Astrophysics since 2015. He currently serves as an Editor of Scientific Reports, reviews for leading journals in mathematical physics and cosmology and for the National Science Centre, and maintains active international collaborations across the United States, Germany, Greece, Estonia, South Africa, Chile, and India—including an Erasmus+-supported lecture series at the University of Tartu and a presentation at the Geometric Foundations of Gravity conference.

Dr Debayan Ghosh

Founder -Chairman & Managing Director of Epygen Group, Mr. Ghosh brings over thirty years of international leadership across the USA, UAE, and India, translating advanced biotechnology research into scalable, real-world solutions spanning healthcare, environmental sustainability, and industrial biotechnology. Under his strategic vision, Epygen Group has built a formidable global footprint, with state-of-the-art research and innovation centres in Dubai, India, and the United States, delivering science-driven solutions of meaningful commercial and societal impact and positioning the Group at the forefront of emerging biotech advancements. An accomplished scientist and corporate strategist, he holds an M.Tech in Biotechnology, complemented by executive leadership credentials from IIM, and is a recognized innovator and respected contributor to the global scientific community, having authored numerous international scientific publications and secured multiple U.S. patents—reflecting a sustained commitment to research excellence and technological progress.

Dr Yashmin Choudhury

Professor in the Department of Biotechnology, Assam University, Silchar, Dr. Choudhury earned her doctorate from the Department of Biochemistry, North-Eastern Hill University, Shillong, followed by postdoctoral training at the Beatson Institute for Cancer Research, United Kingdom. Her research spans the identification of biomarkers for head and neck cancer, drug-repurposing approaches to cancer therapeutics, genomic studies on betel quid and tobacco dependence in the Northeast Indian population, and biopeptide discovery from insect sources. She has authored 70 peer-reviewed articles and book chapters, amassing 1,144 citations with an H-index of 17 and an i10-index of 30, and has completed five extramurally funded research projects with three currently ongoing, mentoring 12 Ph.D. scholars, 2 postdoctoral research associates, and 45 dissertation students along the way. Her research group has been recognized as a Unit of Excellence in biotechnology research in Northeast India by the DBT, Government of India, under its U-Excel Scheme. Her honours include the DBT Overseas Associateship for the North-Eastern Region (2012–2013), the prestigious INSA Teacher Award (2021) from the Indian National Science Academy, and the Women Scientist Award (2025) from the Indian Immunology Society.

Dr Lalzo S. Thangjom

Assistant Professor in the Department of Social Work at Assam University, Silchar, Dr. Thangjom earned his Ph.D. for a doctoral study on HIV/AIDS mitigation policies in Manipur. His interdisciplinary research portfolio spans public health, substance abuse, sustainable development, indigenous communities, social policy, and rural livelihoods, with a strong focus on marginalized populations in Northeast India. He has authored numerous publications on HIV/AIDS mitigation, rehabilitation, indigenous food systems, and community development, and served as Convenor of the North East International Sustainable Summit at Assam University. He has contributed to edited volumes on sustainable development and remains active in academic and professional bodies.

Dr Deigracia Nongkynrih

Associate Professor in the Department of Economics at North-Eastern Hill University (NEHU), Shillong, Dr. Nongkynrih holds an M.A. in Economics (2002) and a Ph.D. (2011) from NEHU, the latter on women's workforce participation in India. She joined NEHU as Assistant Professor in 2006, following a tenure at St. Edmund's College, Shillong, and was promoted to Associate Professor in 2017. Her research specializes in labour economics, gender studies, rural development, and the regional economy of Northeast India, including studies on female domestic workers, rural employment dynamics, and labour supply projections. She served as Programme Coordinator of the NSS Cell at NEHU (2019–2022) and is affiliated with the North East Economic Association, the Indian Economic Association, and the Indian Society for Training and Development, having supervised doctoral and postgraduate scholars.

Dr Moses Newme

Assistant Professor and Assistant Dean (Academics), School of Social Sciences, The Assam Royal Global University, Guwahati, Dr. Newme completed his BSW, MSW, and Ph.D. at Assam University, Silchar, as a recipient of the UGC-NET Junior Research Fellowship. His research examines rural livelihoods, tribal development, social inclusion, and community participation, with particular emphasis on Northeast India's indigenous and rural communities. Alongside his scholarly contributions, he maintains a strong commitment to community outreach and development initiatives, reflecting his belief in the transformative power of education and research.

Dr T. Luithuiwung Awungshi

Associate Professor, Faculty of Social Sciences and Humanities, Assam down town University, Guwahati, Dr. Awungshi holds a doctoral degree in Social Work from Assam University, Silchar, focused on child rights, social protection, and community development. With over a decade of experience in teaching and research, his interests span child rights and protection, tribal studies, sustainable livelihoods, social policy, and participatory social work practice. He has authored numerous publications on child rights governance, community participation, and indigenous knowledge systems, presented at national and international conferences, and serves as a journal reviewer while contributing to curriculum development and student mentoring.

Dr Bibharani Swargiary

Assistant Professor (Senior), Department of Social Work, Assam Don Bosco University, Guwahati, since 2018, Dr. Swargiary previously taught at the University of Science and Technology Meghalaya (2016–2018). She holds a Master's in Social Work from the Tata Institute of Social Sciences (TISS), Mumbai, and a doctoral degree in Social Work, with research centred on tribal and indigenous social work, conflict and peace studies, gender studies, and community development—particularly the experiences of tribal and Adivasi women affected by conflict in Northeast India. She has worked with the North Eastern Social Research Centre, Guwahati, and the Foundation for Social Transformation, served on the Departmental Board of Studies at Assam Don Bosco University, and participated in the Erasmus⁺ KA171 mobility programme at Frankfurt University of Applied Sciences, Germany (2026).

Mr Alok John

A distinguished academic leader, management expert, trainer, and consultant with extensive experience in higher education, institutional development, and industry engagement. He currently serves as the Dean of NICCS and Director of the Mother Veronica Excellence and Innovation Centre at Patna Women's College (Autonomous). Previously, he played a pivotal role in the establishment and growth of the IIM, Bodh Gaya. He served at IIM Calcutta and Hindalco Industries Ltd. Presently pursuing his Ph.D. in HRM from the NIT, Patna, and is a qualified professional in both Management and Human Resource Management/Personnel Management & Industrial Relations. An accomplished researcher, he has published extensively in reputed national and international journals and has been invited as a resource person by prestigious organizations including the National Commission for Women (NCW), Department of Science & Technology (DST), Government of India, Federation of Indian Export Organisations (FIEO), IRCTC, TATA Motors, and several premier academic institutions. He has received several prestigious recognitions, including the Most Iconic Educational Leader Award by Times Ascent and the World HRD Congress, the Institutional Leadership Award, and the Outstanding Performance Award for his exceptional contributions to academic excellence, innovation, entrepreneurship, and institutional collaborations.

Biodiversity Crisis in India: Drivers, Impacts, and Policy Gaps

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ABSTRACT

India is one of the world's megadiverse countries, supporting roughly 7-8% of all known species although making up only 2.4% of the planet's land area. However, the nation's biodiversity loss has accelerated due to both environmental change and economic development. The IUCN has classified over 12% of assessed animal species as endangered, and about 90% of the land within India's four global biodiversity hotspots has already been degraded. Although earlier studies have examined specific threats to biodiversity in India, a comprehensive understanding of how these interconnected factors collectively drive biodiversity decline remains limited. This review comprehensively evaluates the major causes of biodiversity loss, including land-use change, mining, infrastructure expansion, pollution, climate change, overexploitation, invasive alien species, and habitat fragmentation. Emphasis is placed on forest diversion, ecosystem degradation, pollution-driven ecological stress, climate change induced habitat alterations, and the growing incidence of human-wildlife conflict. By integrating findings from scientific studies, conservation assessments, monitoring programmes, and policy records, the review provides a national-scale perspective on biodiversity decline in India and presents an evidence-based framework to support conservation planning, environmental governance, and sustainable development strategies.

KEYWORDS: Anthropogenic disturbance, Ecological fragmentation, Environmental governance, Habitat degradation, Species decline.

INTRODUCTION

Biodiversity, the variety of life on Earth that includes genetic, species, and ecosystem diversity, underpins ecosystem services that are essential for human well-being, such as pollination, water purification, and climate regulation. India is exceptionally rich in biodiversity, and despite occupying only about 2.4% of the world's land area, it harbours nearly 7 to 8% of the planet's recorded species (National Biodiversity, 2020). It is one of only 17 megadiverse countries globally, supporting an estimated 96,000 species of animals and 47,000 species of plants. Four global biodiversity hotspots fall wholly or partially within India, including the Himalaya and Indo-Burma region encompassing Northeast India, the Western Ghats, and Sundaland represented by the Andaman Islands. These regions are

characterised by exceptionally high levels of endemism and many threatened species (National Biodiversity, 2020). Paradoxically, India's rich biological heritage is under severe pressure. Habitat loss from development, pollution, overexploitation, invasive species and climate change is driving sharp declines in many taxa (CSE, INDIA, 2021; Research Matters, 2025). India's biodiversity crisis is part of a broader global trend of biodiversity decline highlighted by recent international assessments. The inter-governmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) has warned that up to one million species worldwide face extinction due to human activities, while the Convention on Biological Diversity's Kunming-Montreal Global Biodiversity Framework (2022) has

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established ambitious targets for halting biodiversity loss, restoring degraded ecosystems, and protecting at least 30% of terrestrial and marine areas by 2030 (IPBES, 2019; CBD, 2026). Evaluating India's biodiversity trajectory is therefore essential not only for national conservation planning but also for assessing progress toward global biodiversity commitments. Recent surveys report alarming trends, showing that more than half of the bird species for which long-term data exist are declining in population, and dozens of Indian species are already extinct or endangered (Eapen, 2020). The State of India's Birds Report 2020, analysing 867 bird species, found that 52% of 261 species with long-term data have declined since 2000, with 22% declining sharply. Alarmingly, among 146 species assessed for recent trends, nearly 80% are declining, and about 50% are in steep decline. In just five years, the number of Indian bird species at high risk of extinction rose from 82 to 101. Some species face near collapse, with the Finn's Weaver declining by up to 94% and fewer than 500 individuals remaining in India (Eapen, 2020). Conservation gaps extend well beyond avian species and reveal significant policy shortcomings. In India, 159 freshwater fish species are threatened with extinction, yet none are included under the protection. Habitat loss remains a central driver of biodiversity decline. Since 2015, approvals have been granted for the felling of nearly 11 million trees, and between 2019 and 2020, about 692 hectares of protected wildlife habitat were cleared for infrastructure projects. These trends mirror a broaden global crisis, with wildlife approximately 13 per cent are classified as facing a high risk of extinction. This includes 180 critically endangered species, many of which still lack adequate legal of the Wildlife Protection Act. More broadly, of the 8,664 species assessed in India by the International Union for Conservation of Nature (IUCN) Red List, populations have declined by 68 per cent since 1970, placing India among the countries at the highest risk of biodiversity collapse (Eapen, 2020).

An India-specific assessment is particularly important because the country simultaneously supports exceptional biological diversity, a large and growing human population, and one of the world's fastest-growing economies. The resulting pressures from infrastructure expansion, urbanisation, energy development, and resource extraction create unique conservation challenges that differ from those faced by many other megadiverse nations. Furthermore, India plays a critical role in achieving global biodiversity conservation goals, as the status of its ecosystems directly influences regional ecological stability, climate resilience, and the persistence of numerous endemic species. India has already lost around 90% of the area within its four global biodiversity hotspots, signalling an extreme erosion of its most species-rich landscapes. The Indo-Burma hotspot has suffered the greatest damage, with natural vegetation shrinking from 2,373,057 sq. km to just 118,653 sq. km a staggering 95% loss. Consequently, at least 25 species have gone extinct within these hotspots alone. According to the IUCN Red List, 1,212 animal species in India are monitored, and over 12% are endangered. Among the 148 endangered species, the crisis is particularly acute for vertebrates, including 69 mammals, 456 amphibians, and 23 reptiles, highlighting the disproportionate vulnerability of amphibians (CSEINDIA, 2021).

This paper reviews the causes and patterns of biodiversity loss in India, focusing on human-driven land-use change and ecological stressors. We stress that India's status as a megadiverse nation is under threat and outline the objectives of this review, which are to synthesise recent evidence on biodiversity decline, identify major anthropogenic pressures ranging from forest diversion and pollution to climate change, and examine policy and management responses. By surveying the literature and government data from the past decade, we aim to provide a thorough overview of how India's development trajectory is impacting its biological wealth and what measures could mitigate these trends.

Overview of Biodiversity in India

India is officially divided into ten biogeographic zones (Trans-Himalayan, Himalayan, Desert, Semi-Arid, Western Ghats, Deccan Peninsula, Gangetic Plains, North-East, Coasts, and Islands). Each zone encompasses distinct climates and ecosystems, ranging from the alpine and temperate forests of the Himalayas to the tropical rainforests and montane grasslands of the Western Ghats, and from the dry thorny scrub of the Thar Desert to the mangrove-rich coastal wetlands. These zones are further subdivided into 27 biogeographic provinces. For example, the Himalayan zone contains subtropical forests at lower elevations and coniferous and alpine ecosystems higher up, while the Western Ghats (a UNESCO World Heritage site) run along India's western coast and support lush tropical evergreen forests with exceptionally high endemism. The Gangetic Plains, Northeast India, and islands such as the Andaman and Nicobar Islands each support distinct and unique assemblages of species (Sharma, 2025). Two of India's zones, the Western Ghats and the Eastern Himalaya region, are internationally recognised biodiversity hotspots (among the 36 globally) due to their extraordinary endemism and extensive habitat loss. For example, the Western Ghats cover only ~4% of India's area but contain about 15,000 plant species, and nearly 4,000 of which are endemic to the region. The Eastern Himalaya (part of the larger Himalayan hotspot) also hosts hundreds of endemic plants and animals adapted to the montane environment. Aside from hotspots, many other habitats in India (e.g., central Indian forests, Gangetic wetlands, and coastal mangroves) are highly biodiverse (National Biodiversity, 2020; Sharma, 2025). Despite this richness, many Indian species are under threat. Of the roughly 1,212 Indian vertebrate species monitored by IUCN, over 12% are listed as threatened (endangered or critically endangered). In India's hotspot regions alone, at least 25 species have already gone extinct, and about one in eight of the assessed species is endangered

(National Biodiversity, 2020). Iconic mammals like Bengal tigers, Asiatic lions, one-horned rhinoceros, Asian elephants, and snow leopards are threatened by habitat loss and poaching (Lai, 2024). Many amphibians and birds with restricted distributions, such as forest frogs and vultures, are also in decline. Overall, India's once-rich baseline biodiversity is being steadily eroded, as protected-area inventories and ecological surveys increasingly show that formerly common species are disappearing, becoming fragmented into small populations, or shifting their geographic ranges (WWF India, 2024).

Measuring Biodiversity Loss in India

Quantifying trends in biodiversity is challenging but crucial. India relies on multiple data sources, such as the IUCN Red List, which provides global threat assessments for some species, and it also produces a National Red List for plants and selected animal groups. The government's ENVIS (Environmental Information System) network and the Wildlife Institute of India compile biodiversity data, while the Forest Survey of India (FSI) publishes biennial Forest Cover reports that track changes in forest area and type. The latest report by the Ministry of Environment, Forest and Climate Change (MoEFCC) (2024) states that India's forest and tree cover combined is about 25.17% of the country's land. Although overall forest cover has shown slight net increases in recent decades (due in part to plantations and regrowth), this metric masks continuing loss of old-growth forests and wildlife habitat in many regions (Pandey, 2024a). According to the Universal Group of Institutions (2024), tree cover showed a significant increase of 1,289 sq. km, reflecting a sharp 0.5% growth in the last two years. In contrast, forest cover growth remains marginal, increasing by only 0.05% since 2021. Over the past two decades, the growth in tree cover has been driven primarily by plantations, whereas natural forest cover has shown little to no significant increase. Between 2021 and 2023, India lost 3,913 sq. km of dense forests, consistent with a 20-year trend of steady degradation. From 2003 to 2023, 24,651

sq. km of dense forests were destroyed, half the size of Punjab. Between 2014 and 2024, Mizoram experienced a substantial decline in forest resources, losing approximately 270 thousand hectares of forest cover over the ten-year period (Table 1). Although some losses were offset by plantations, natural dense forests are being replaced by monoculture plantations, raising ecological concerns. Reclassifying plantations as dense forests artificially boosts reported growth figures and obscures the true extent of forest degradation. While plantations help meet carbon targets faster, their frequent harvesting undermines long-term climate goals. Experts argue the report counts plantations,

roadside trees, orchards, and urban patches as “forest cover”. This inflates numbers and masks the decline of natural, biodiverse forests. Environmental lawyer Ritwick Dutta noted contradictions, explaining that roadside plantations are not considered forests under the Forest Conservation Act 1980 but are counted as forest cover in the India State of Forest Report (Aggarwal, 2022a; Pandey, 2024a). Between 2014 and 2024, India experienced a loss of 1.5 million hectares of tree cover, representing 4% of its tree cover recorded in 2000. This decline resulted in an estimated 830 million tonnes of carbon dioxide equivalent emissions (GFW, 2026) (Figure 1).

Rank	States/UTs	Forest cover Loss
1	Mizoram	270
2	Assam	200
3	Manipur	180
4	Meghalaya	170
5	Nagaland	160
6	Tripura	100
7	Odisha	89
8	Kerala	78
9	Arunachal Pradesh	67
10	Karnataka	32

Table 1: State wise tree cover loss in India in thousand hectares across selected states from 2014-2024. Source: <https://www.globalforestwatch.org/>

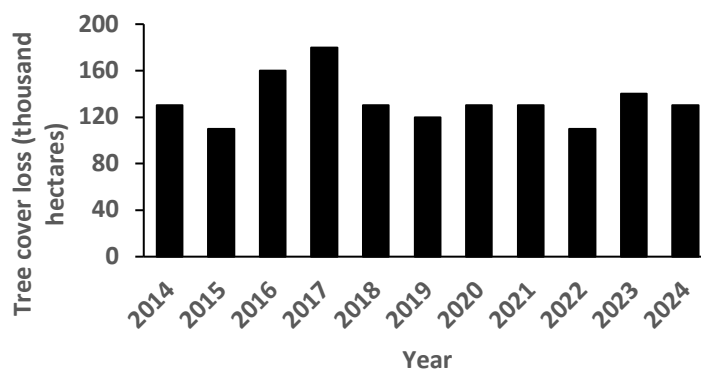


Figure 1. Annual tree cover loss in India from 2014 to 2024 expressed in thousand hectares showing year wise variation in forest decline. Source: <https://www.globalforestwatch.org/>

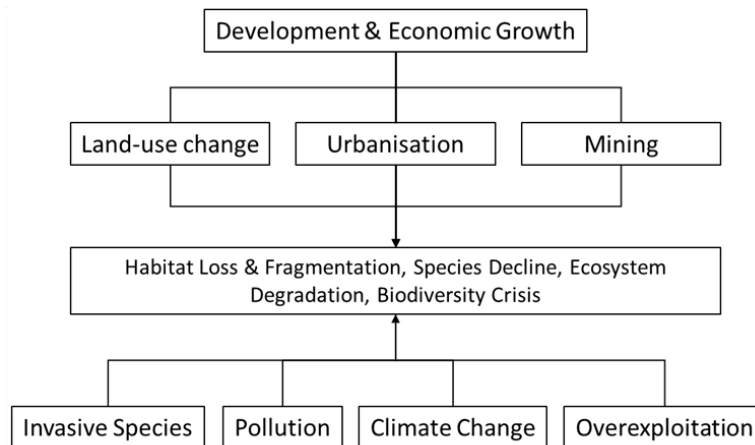


Figure 2. Conceptual framework illustrating the major anthropogenic drivers of biodiversity loss in India.

Citizen science initiatives and NGO-led research have helped bridge major data gaps in biodiversity monitoring. Analyses of bird population trends using eBird checklist data illustrate this clearly. The State of India's Birds (SoIB) 2023 evaluated 942 bird species and found long-term declines in 204 species, with 142 species showing ongoing declines (Viswanathan et al., 2025). Earlier, the SoIB 2020 reported that among 261 species with sufficient long-term data, 52% had declined since 2000, including 22% showing steep declines. This pattern has intensified, with SoIB 2023 indicating 60% of species in long-term decline and 40% in current decline (Bird Count India, 2023).

These results point to widespread deterioration, affecting even once-common birds, with species feeding on vertebrates or invertebrates declining most rapidly (Viswanathan et al., 2025). Comparable trends are emerging from targeted studies on plants, butterflies, and freshwater taxa, which report rapid local losses despite limited systematic monitoring. Nearly 23% of freshwater species remain data deficient, suggesting that actual extinction rates are likely underestimated (Sayer et al., 2025). Regional assessments further confirm a sharp decline in freshwater faunal diversity across India, with many species now facing a high risk of extinction (Dimri et al., 2025).

MAJOR DRIVERS AND IMPACTS OF BIODIVERSITY LOSS IN INDIA

Although biodiversity loss in India is driven by multiple interacting pressures, available evidence indicates that land-use change and habitat loss remain the dominant drivers, primarily through forest diversion, mining, infrastructure expansion, and urbanisation. These pressures are followed by pollution, climate change, overexploitation of biological resources, invasive alien species, and habitat fragmentation (Figure 2). Importantly, these drivers rarely operate in isolation. For example, road construction can simultaneously cause habitat loss, fragmentation, pollution, and facilitate the spread of invasive species.

Climate change further amplifies the impacts of existing stressors by reducing ecosystem resilience and accelerating species declines. Therefore, biodiversity loss in India should be viewed as the outcome of interacting and mutually reinforcing pressures rather than independent threats. Biodiversity loss in India is driven by a complex set of interacting pressures that are reshaping ecosystems across regions and taxa. The following sections examine the principal drivers of biodiversity loss in India and their ecological impacts.

1. Land-Use Change and Deforestation Driven by Development Projects

Land use change, particularly the conversion of natural forests to other uses, is the dominant

driver of habitat loss in India. This section examines the multiple ways in which development projects sanctioned by the government or carried out illegally lead to forest clearance and ecosystem degradation.

1.1 Government-Permitted Deforestation

Under the Indian Forest (Conservation) Act, 1980, now the Van (Sanrakshan Evam Samvardhan) Adhiniyam, any diversion of forest land for non-forest uses (mining, roads, reservoirs, etc.) requires central approval. Despite this, hundreds of thousands of hectares have been cleared. Government data show that 173,984.3 hectares of forest land were approved for diversion to “non-forestry” projects between 2014 and 2024 (DTE, 2025; Nandi, 2025). The largest categories of approved diversion in that decade were mining/quarrying (> 40,000 ha) and hydropower/irrigation projects (> 40,000 ha). Linear infrastructure is a major driver of forest diversion. Between 2014 and 2024, approvals covered approximately 30,606 ha for roads and about 17,233 ha for power transmission lines. Railway expansion, involving around 8,000 ha, and defence installations, covering nearly 14,968 ha, were also significant, alongside smaller allocations for industry and urban-related uses. Overall, forest clearances for infrastructure and industrial projects increased by more than 150% between 2014 and 2023 (The Assam Tribune, 2025). These figures indicate massive habitat fragmentation under official sanction. For example, new highways through central India have bisected corridors once used by tigers and elephants, and large dam projects have flooded valleys that hosted diverse forest communities. Urban projects expanding airports, rail networks, and “smart city” zones routinely involve forest land diversion (Variyar, 2021; SANDRP, 2025). Compensatory afforestation is meant to offset forest loss, but in practice it often falls short. States struggle to secure appropriate land, so plantations are frequently created far from the original sites, weakening their ecological value. While new trees may restore canopy cover, they cannot replicate the biodiversity and

complexity of mature forests. Even where compensatory afforestation is mandated, it often results in monoculture plantations far from the lost habitat. Large land requirements also raise risks of community displacement, procedural bypasses, and land banking. Critics argue that the policy can end up legitimising forest diversion rather than preventing it. In Delhi, limited non-forest land has pushed authorities to consider planting in neighbouring states, a move widely criticised as ecologically ineffective and counterproductive (CUES, 2021; Hindustan Times, 2021). The cumulative effect is a piecemeal undermining of India’s forest cover and connectivity under the guise of development.

1.2 Mining Expansion and Habitat Destruction

Mining represents one of the most consequential forms of approved land use change in India, as vast deposits of coal and metallic ores lie beneath forested regions in states such as Chhattisgarh, Odisha, Jharkhand, and Karnataka. Official data showing tens of thousands of hectares diverted for mining reflects its central role in deforestation. Although national reports often cite increasing forest cover, large tracts of dense forests have been cleared for extraction. Both legal and illegal operations, frequently enabled by weak oversight and political backing, have expanded across mineral-rich regions, including Madhya Pradesh and Maharashtra (WRM, 2019; Dhankhar, 2025). The Hasdeo Arand illustrates the conflict, where mining approvals proceeded despite ecological sensitivity, wildlife corridor value, and community resistance. Safeguards under the Forest Rights Act are often diluted, and funds meant for ecological restoration are diverted toward relocations rather than regeneration. The Aravalli Range across Rajasthan, Haryana, and Delhi faces similar degradation from illegal stone extraction. Vegetation loss, soil erosion, groundwater decline, and advancing desertification threaten livelihoods and biodiversity. Open-pit mines and associated infrastructure fragment habitats, disrupt wildlife corridors, and shrink common

lands, intensifying ecological stress and social conflict across forested landscapes (Dhankhar, 2025).

1.3 Absence of Meaningful Compensatory Afforestation

Indian law mandates that diversion of forest land for non-forest purposes be accompanied by compensatory afforestation on an equivalent or larger area, together with payment of net present value to account for the loss of ecosystem services. Under India's forest governance framework, these financial contributions are collected and managed through the Compensatory Afforestation Fund Act, 2016, which is intended to ensure ecological offsetting of forest diversion (National CAMPA online, 2026). While this framework is designed to balance development with conservation, its practical outcomes have been widely questioned. A Supreme Court-appointed committee and several audits, including assessments based on Comptroller and Auditor General findings, have revealed persistent implementation failures such as delays in land transfer, absence of actual plantations, use of community lands for afforestation, and completion of plantations on only a small fraction of the mandated area. Consequently, compensatory plantations have not matched the ecological functions of natural forests, leading to an overall decline in forest quality and extent despite formal compliance (Aggarwal, 2022b). Further analyses show that many CA initiatives prioritise fast-growing commercial species such as eucalyptus, acacia, and teak, often planted as monocultures on marginal lands. These plantations deplete groundwater, degrade soils, and support limited biodiversity, failing to restore original forest structure or wildlife habitat (Nitnaware, 2026). Concerns have intensified following recent policy changes that allow large commercial plantations to be classified as forestry, thereby exempting them from CA and NPV requirements. Conservationists argue that this shift effectively replaces natural forests with tree farms, weakening ecological safeguards and undermining genuine forest conservation

(INSIGHTS IAS, 2026; NORTHEAST NOW, 2026; Rahul, 2023). Thus, the legal framework still links clearance to replanting, but implementation has often failed to preserve ecosystems.

2. Urbanisation and Infrastructure Development

Rapid and inadequately planned urbanisation has emerged as a dominant driver of environmental transformation in India's fragile ecosystems, particularly in the northwest Himalayas and the Western Ghats. In the Lesser Himalayas of Uttarakhand and Himachal Pradesh, urban expansion has intensified land use within ecologically sensitive landscapes. Remote sensing analysis from Nainital district shows an 11% decline in natural forest cover between 1991 and 2023, accompanied by a more than 100% increase in built-up area. Much of this growth has occurred over forests, agricultural land, spring sheds, floodplains, and steep slopes, leading to a 17% reduction in groundwater recharge, 35% depletion of natural springs, 11% loss of urban wetlands, and a 27% decline in biodiversity. Uttarakhand now ranks as the fastest urbanising Himalayan state, with over 30% of its population residing in urban areas compared to a regional average of 26%, while urban growth has encroached upon 11% of agricultural land and 9% of forests. Comparable land cover changes linked to urbanisation, timber extraction, and mining have also been documented in Kashmir, with projections indicating continued woodland decline in the Northwest Himalayas by 2030 (Pandey, 2024b). Across India, rapid urban population growth has driven cities to expand into surrounding natural habitats. Major metropolitan regions such as Delhi NCR, Mumbai, Bengaluru, and Hyderabad have experienced extensive sprawl, resulting in the large-scale loss of peri-urban ecosystems, including wetlands, lakes, and green corridors (Pandey, 2024b). In Delhi NCR, the disappearance of large numbers of wetlands has been associated with reduced groundwater recharge, increased flood risk, and intensifying urban heat island effects, as natural drainage

basins are replaced by impervious surfaces (Singh et al., 2023; Pandey, 2025; Yadav et al., 2025). Urban infrastructure development further fragments habitats by dissecting wildlife corridors through highways, ring roads, industrial zones, and residential projects. As forest patches become isolated, large mammals such as leopards and tigers are increasingly forced into human-dominated landscapes, resulting in rising wildlife sightings and escalating human-wildlife conflict, genetic bottlenecks, and ecological stress along urban fringes (Rajani, 2025; Singh et al., 2025a).

3. Pollution as a Driver of Biodiversity Loss

3.1 Air Pollution

Air pollution has emerged as a significant driver of biodiversity decline in India, causing direct physiological injury and disrupting ecological interactions, particularly in urban hotspots (Goud, 2024). Evidence from a four-year investigation by the National Centre for Biological Sciences highlights the severity of this threat.

The study analysed 1,820 wild giant Asian honeybees (*Apis dorsata*) across rural to highly polluted sites in Bengaluru and reported stark mortality differences. Average PM10 levels were 28.32 µg per m³ in rural areas but exceeded 100 µg per m³ at the most polluted sites, surpassing national standards at six of seven locations. In polluted environments, 80% of bees died within 24 hours and all perished within 1.5 days, whereas some rural bees survived up to four days. Exposed bees showed reduced foraging, irregular heart function, suppressed immunity, altered gene expression, and body surfaces coated with arsenic, lead, and tungsten. Laboratory-reared *Drosophila melanogaster* displayed comparable physiological disruptions under similar exposure conditions (Rao, 2020; Thimmegowda et al., 2020). Air pollutants further disrupt pollination by degrading floral scents and pheromonal signals. Ozone and nitrogen oxides can reduce flower visitation by up to 90% and pollination success by 31%, impairing insect communication and reproduction (Duque and Stefan Deventer,

2024; Kimbrough, 2022). Vegetation also experiences substantial injury. Ozone, sulphur dioxide, nitrogen oxides, and particulate matter impair photosynthesis, damage leaf tissues, disrupt nutrient uptake, and delay flowering, resulting in 5 to 10% crop yield losses and reduced carbon sequestration (González Medina et al., 2025; Singh et al., 2025b). Vertebrates face respiratory and systemic impacts from inhaling PM2.5, ozone, nitrogen oxides, and sulphur dioxide, leading to inflammation, cardiovascular strain, and organ damage (WHO, 2026). Globally, air pollution contributed to 6.7 million deaths in 2019 and poses comparable risks to wildlife, including reproductive decline in birds and developmental deformities in amphibians (WHO, 2024; Ghorani Azam et al., 2016).

3.2 Water Pollution

Rivers and lakes in India are heavily contaminated by untreated sewage, agricultural runoff, and industrial effluents (from tanneries, textiles, mining, etc.). Recent reports from the Central Pollution Control Board (CPCB) and government sources confirm severe contamination in Indian rivers from untreated sewage, agricultural runoff, and industrial effluents (tanneries, textiles, and mining). Major rivers like the Ganga, Yamuna, and Sabarmati consistently fail water quality standards. Based on Biochemical Oxygen Demand (BOD), some river stretches were categorised under Priority 1 (BOD > 30 mg/L), indicating” NOT “Based on Biochemical Oxygen Demand (BOD), some river stretches were categorised under Priority 1 (BOD > 30 mg/L) based on Biochemical Oxygen Demand(BOD), indicating severe organic pollution (Vision IAS, 2025).

Eutrophication and toxic pollution devastate aquatic ecosystems, with fish and amphibians affected by oxygen depletion and heavy metal contamination, while even the rare Ganges River dolphin and Indus River dolphin face heightened risk from the loss of clean habitats and adequate prey (Sinha & Kannan, 2014). Polluted wetlands lose their aquatic plants and invertebrates, reducing food for migratory

birds. Contaminants undergo biomagnification, with pesticides from agricultural fields detected in river fish and even in human breast milk in urban areas, highlighting the profound risks posed to food webs and ecosystem health.

3.3 Soil Pollution and Agrochemicals

Intensive farming has introduced chemical stressors into India's landscapes. Insecticide and fertiliser runoff disrupt soil biota and non-target insects. For instance, neonicotinoid pesticides (widely used on cotton and vegetables) have been implicated in damaging pollinators such as bees and butterflies, though large-scale, India-specific studies are sparse (Chandrasekar et al., 2022). Imbalanced NPK (7.7:3.1:1 vs ideal 4:2:1) from intensive farming alters soil chemistry, reduces microbial diversity/populations, and depletes SOC. Overapplication of fertilisers alters soil chemistry, reducing microbial diversity and earthworm populations that are vital for soil fertility (Jat et al., 2021). Cumulatively, soil pollution reduces the carrying capacity of agricultural margins and woodlots for wildlife. There is growing evidence globally and some indications from India that heavy pesticide use contributes to the decline of beneficial insects (pollinators, predators) and the collapse of food chains (Spence et al., 2025). Landfilling of toxic waste and industrial slag, furthermore, destroys vegetation and alters local hydrology. Thus, agrochemical and waste pollution are subtle but pervasive drivers of habitat degradation in both rural and peri-urban India (Goswami & Basak, 2021).

4. Climate Change Intensified by Human Activity

The Himalayan region, which is geologically young and highly fragile, has undergone rapid warming during the 21st century. Temperature increases range from 0.15°C to 0.60°C per decade, a rate substantially higher than the global average of 0.74°C per century, affecting monsoon patterns and leading to more frequent extreme heat and drought. In the Himalayas, accelerated glacier melt threatens alpine ecosystems and river flow regimes downstream, altering freshwater habitats

(Ahmed, 2025). Due to an increase in global temperature, terrestrial species are shifting their ranges. Case studies, such as the poleward expansion of the fall armyworm (*Spodoptera frugiperda*), phenological shifts in aphids, and increased bark beetle outbreaks in warming forests (Mehla et al., 2025). India's 7,500 km coastline is recognised as among the most vulnerable globally to sea-level rise, storms, and erosion, prompting the MoEFCC to map a national "hazard line" for climate-driven periodic bleaching events (Shohidullah Miah, 2015; MOEFCC, 2018).

Coastal and marine ecosystems are particularly at risk. India's long coastline is among the most vulnerable to climate impacts. Sea surface temperatures in the Indian Ocean have warmed by ~1°C since the 1950s, causing coral bleaching and habitat loss (Wenegrat et al., 2022). Given that reefs support many fish and invertebrates, this portends declines in marine biodiversity and fishery yields. Mangrove forests, another rich ecosystem (e.g., the Sundarbans), face rising sea levels and cyclonic storms. The Sundarbans' mangroves buffer India's largest mangrove delta, but saltwater inundation and severe cyclones (cyclone Amphan in 2020, for example) have degraded sections of it. Studies note that increased salinity stress and storm damage are hindering mangrove regeneration, which in turn jeopardises the myriad species (from Bengal tigers to estuarine fish) that depend on them (Chowdhury et al., 2023; ZCA, 2022). Marine species are also shifting due to climate change. Fish like hilsa are changing migratory patterns as ocean warming and river siltation alter breeding grounds (Shohidullah Miah, 2015). Phytoplankton productivity in the Indian Ocean is declining due to stratification from warming, which can ripple up the food chain (Dalpadado et al., 2021). Climate changes driven by human emissions are compounding biodiversity loss by altering habitats faster than many species can adapt. Many organisms in India are now facing a "double burden" of direct human impacts plus climate stress, pushing already-vulnerable species closer to extinction.

5. Overexploitation of Biological Resources

India's biodiversity is heavily exploited for food, fibre and commerce. Fishing pressure in India is intense, with both marine and inland waters heavily exploited, often beyond sustainable levels. Overfishing and destructive practices (trawling, dynamite) have led to steep declines in large fish stocks and incidental bycatch of turtles, dolphins and seabirds. Illegal, unreported fishing is a concern in the Indian Ocean region (Yadav, 2025). Approximately 56.3% of marine capture

consists of bycatch, and such high rates threaten non-target species such as turtles and seabirds. Unregulated high-seas fishing in the Indian Ocean threatens marine life and food security, with squid catches increasing by up to 830% without effective regulation (WCS, 2023; Johnson, 2020). In forests and wildlands, demand for timber and non-timber products (firewood, medicinal plants, resin, bamboo, etc.) drives unsustainable harvests.

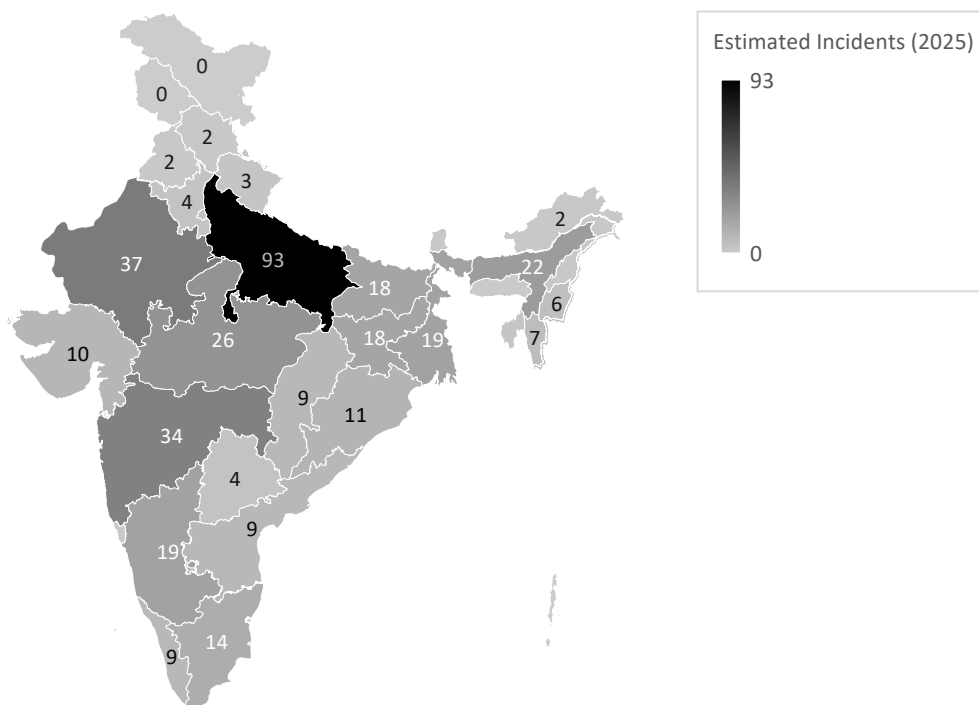


Figure 3. State wise distribution of estimated wildlife poaching and smuggling incidents in India for 2025. Source: <https://indiadatamap.com/>

Local communities rely on these, but commercial logging and charcoal production often exceed regeneration rates. This depletes forest biomass and alters structure, reducing habitat complexity (Forest Trends, 2020). Illegal wildlife trade is another facet of overexploitation. India's forests are source/transit points for poached animals and parts (tiger skins, bones, rhino horns, pangolin scales) going to international markets. Although India has stringent wildlife protection laws, persistent enforcement gaps allow poaching to continue, threatening tigers, leopards, rhinos, and numerous lesser-known species such as musk deer, orchids, and snake venom traded in illicit markets. The illegal pet trade in exotic birds and reptiles further intensifies pressure on already vulnerable populations. Collectively, these activities remove species at rates that exceed their natural capacity for recovery (Rana and Kumar 2023). In 2025, wildlife poaching and smuggling remain serious concerns across the country, with Uttar Pradesh reporting the highest number of recorded incidents (Figure 3).

6. Invasive Alien Species Introduced and Spread by Human Activity

Human altered habitats are highly susceptible to invasions by non-native species, which India has seen in abundance. *Lantana camara* (a shrub from the Americas) has invaded tens of thousands of hectares of Indian forests and grasslands, forming impenetrable thickets that exclude native undergrowth and seedlings. In fact, one study notes *Lantana* has spread into 40% of India's tiger habitat. Other invaders include *Parthenium hysterophorus* (a toxic weed that degrades pastureland), *Prosopis juliflora* (thorny mesquite, overtaking drylands in Rajasthan), *Eichhornia crassipes* (water hyacinth clogging lakes and canals), and *Saccharum spontaneus* (wild sugarcane that suppresses

wetland flora) (Sekar, 2020). These species outcompete local plants for light, nutrients and water, often altering fire regimes and soil chemistry. The result is lower native plant diversity and less food for indigenous herbivores and pollinators. Some ornamental organisms (like *Poecillia reticulata* and *Pterygoplichthys disjunctivus*) also contribute locally. Overall, invasions act as a hidden driver of biodiversity loss. Once invasive species establish, they are costly to remove and often transform entire ecosystems irreversibly (Khambete, 2024).

7. Fragmentation, Isolation & Collapse of Ecosystem Connectivity

Habitat fragmentation is a defining consequence of India's accelerating development. Expanding roads, railways, canals, and mining projects divide once continuous landscapes into small, isolated patches, disrupting ecological connectivity. As habitats shrink and become increasingly separated, wildlife corridors collapse, restricting seasonal migration and limiting access to mates. Species dependent on large, undisturbed forests, such as hoolock gibbons and snow leopards, experience marked declines. Fragmented edges promote soil degradation, greater carbon release, and the spread of invasive plants, including *Lantana camara* and even commercial crops like coffee, into native forests. Sediment runoff from disturbed islands further damages marine ecosystems and coral habitats (Shankar 2024). Many tiger reserves remain tenuously linked by narrow forest strips intersected by highways and plantations. Grid fencing and rail infrastructure obstruct elephant and carnivore movement, while transmission lines hinder arboreal species (Jhala et al., 2021). Fragmentation also reduces gene flow, increasing inbreeding and extinction risk, with dams isolating fish populations (Mondol et al., 2013).

Way Forward — Policy and Management Recommendations

Given the scale of biodiversity loss, urgent policy action is needed. Key recommendations include the following:

- i. **Strengthen Environmental Regulations:** Rather than diluting laws, India must uphold strict norms for forest and wildlife protection. Forest diversion should be minimised, with genuine ecological impact assessments. The recent FCA amendments that favour plantations over forests should be reversed (Saxena, 2024). **Transparent EIA and Public Participation:** All major projects should undergo rigorous, independent environmental impact assessments with public disclosure. Post-facto clearances should be banned. Citizens, scientists, and affected communities must have a real voice in decisions affecting forests, rivers, and wildlife (INSIGHTS IAS, 2025).
 - ii. **Scientific Land-Use Planning:** Use spatial data to identify and protect critical habitats (e.g., remaining old-growth forests, wetlands, mangroves). Zone land for development based on carrying capacity, rather than ad hoc approvals. Integrate biodiversity corridors into city and infrastructure planning (WWF, 2026).
 - iii. **Protect Key Ecosystems:** Special measures should be taken for exceptionally biodiverse regions, for example, by strictly safeguarding the Western Ghats, Eastern Himalaya, Northeastern forests, the Aravalli range, and coastal mangroves. Cancel ecologically harmful projects (like new mines or dams) in sensitive areas (Ghanekar, 2025).
 - iv. **Urban Greening & Pollution Control:** Cities should aggressively expand urban forests, protect remaining wetlands and regulate construction dust and emissions. Stringent air and water quality standards will benefit both people and biodiversity (Vajiram and Ravi, 2025).
 - v. **Climate-Smart Conservation:** Anticipate climate impacts by, for example, protecting altitudinal gradients to allow species migration, preserving genetic diversity (seed banks, gene banks), and restoring degraded forests to enhance carbon sequestration. In coastal zones, strengthen mangrove belts and coral rehabilitation efforts (Hussain et al., 2024).
 - vi. **Community Engagement:** Empower local and indigenous communities as conservation stewards. Co-manage protected areas, ensure fair benefit-sharing from ecosystem services, and uphold tribal land rights in forests (UNDP, 2023).
 - vii. **Wildlife Corridors and Rescue:** Legislatively secure identified wildlife corridors (e.g., elephant corridors) by preventing land conversion. Invest in wildlife crossings on highways and in anti-poaching patrols (WWF, 2026).
 - viii. **Tackle Pollution and Invasives:** Enforce stricter controls on effluent discharge to rivers and industrial emissions. Promote sustainable agriculture to reduce pesticide runoff. Implement invasive species management plans (e.g., remove water hyacinth from lakes and control Prosopis on grasslands) (Lele et al., 2025).
- These and other measures require political will, inter-departmental coordination, and adequate funding. The judicial system (NGT, Supreme Court) and civil society have positive roles in oversight and accountability. International cooperation (e.g., migratory bird conservation, climate aid) will also be important. Ultimately, India must recognise that continued development without ecological limits will undermine long-term prosperity.

CONCLUSION

India stands at a crossroads. Its rapid economic and infrastructural development has lifted millions out of poverty, but it has

also come at a steep ecological cost. As this review shows, virtually every aspect of India's biodiversity, including forests, rivers, coasts, and species, is under mounting strain from human pressures. Land conversion for mining, roads, and urban expansion is fragmenting habitats, while pollution and invasive species are steadily degrading ecosystems, and climate change is further intensifying these pressures by adding another layer of ecological stress. The decline of biodiversity threatens not only wildlife but also India's future: forests and mangroves that buffer floods, insects that pollinate crops, and fisheries that feed coastal communities are all at risk. The solution lies in integrating ecological limits into development planning. This means abiding by environmental laws (not weakening them), conserving large, connected habitats, and investing in restoration. Economic growth and biodiversity conservation can be aligned through green infrastructure and sustainable land use. India's people, from farmers and urban residents to tribal communities, stand to benefit significantly from safeguarding the natural resources and ecosystem services that sustain livelihoods. India's extraordinary biodiversity is an asset and a responsibility. The coming decades will determine whether policies and public will can reverse the current downward trends. Immediate, concerted action is required to ensure that development proceeds in harmony with nature. Only by safeguarding forests, wildlife and water can India preserve the ecological foundations of its future well-being.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Deciphering the Binding Mechanism of Azodyes to *Pseudomonas putida* Laccase enzyme: A Computational Biology approach

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ABSTRACT

Laccase, a metalloenzyme that contains copper which readily oxidizes a wide variety of organic and inorganic substances and could degrade phenolic and non-phenolic compounds. This property could possibly be exploited to detoxify a varied range of environmental pollutants including commercially important dyes viz., Crystal Violet, Congo Red, Indigo, Direct Blue 9 etc. These dyes are very important commercially, but their disposal becomes an issue as it pollutes the water sources wherein, they are readily thrown. Enzymes from bacteria and cyanobacteria have shown much promising results in degrading the dyes into simpler compounds and their decolorization makes them less harmful so they can be degraded by nature subsequently. In our current study, we have tried to model the structural interaction of Laccase enzyme derived from *Pseudomonas putida* and these industrial dyes, which in turn gives us insights into the potential of degrading these harmful dyes for downstream wastewater treatment. This study can be further taken into consideration to learn more about bacterial laccase structural features and its detoxifying activities to remove hazardous environmental pollutants.

KEYWORDS: Laccase, Multiple Sequence Alignment, domains and motifs, homology modelling, molecular docking, *Pseudomonas putida*.

INTRODUCTION

Rapid industrialization and modernization have led to the extensive release of untreated industrial effluents into the environment, making wastewater pollution one of the most pressing environmental challenges worldwide. Among various industrial pollutants, synthetic dyes discharged from textile, paper, leather and dye manufacturing industries constitute a major source of aquatic contamination due to their persistence, toxicity and resistance to biodegradation (Thakuria et al., 2015). The continuous discharge of dye-containing effluents not only imparts intense coloration to water bodies but also reduces light penetration, disrupts aquatic ecosystems and poses serious health risks to humans and other living organisms. Consequently, there is an urgent

need to develop sustainable and environmentally friendly strategies for the treatment of dye-contaminated wastewater. The synthetic dye decomposition techniques such as adsorption on various sorbents, chemical decomposition by oxidation, photodegradation and microbiological decolouration are developed (Forgacs et al., 2004).

Microorganisms have emerged as promising agents for the biodegradation of recalcitrant organic pollutants owing to their remarkable metabolic diversity and adaptability. Soil bacteria hold a high contribution in the catalysis of aerobic treatment of the wastes from chemical plants (Levine, 1991). Anaerobic bacteria such as *Clostridium* species demonstrated treatment of various azo dyes

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without leading to mutagenicity in the *Salmonella typhimurium* strains TA98 and TAI00 (Raffi et al., 1997). Most of the dyes and the chemicals were observed to be utilized by an alkalophilic microorganisms' consortium parallel to nitrogen consumption by the consortia for growth (Brown & De Vito, 1993). Among them, *Pseudomonas putida*, a Gram-negative bacterium widely distributed in soil and aquatic environments, has attracted considerable attention because of its exceptional ability to metabolize a broad spectrum of aromatic compounds and industrial contaminants. This metabolic versatility is attributed to its diverse enzymatic machinery, enabling the degradation of numerous xenobiotic compounds, including synthetic dyes. Although azoreductases have been extensively investigated for their role in azo dye degradation, increasing awareness has recently been focussed towards bacterial laccases as multifunctional oxidative enzymes capable of degrading structurally diverse pollutants.

Laccases (EC 1.10.3.2) are multicopper oxidoreductase enzymes that catalyse the oxidation of a wide range of phenolic and non-phenolic substrates while simultaneously reducing molecular oxygen to water (Madhavi and Lele, 2009). Their broad substrate specificity, coupled with their ability to catalyse oxidation without requiring additional cofactors, has made laccases highly attractive for numerous biotechnological and environmental applications. Compared with fungal laccases, bacterial laccases exhibit several advantageous characteristics, including greater thermal stability, wider pH tolerance, enhanced resistance to harsh environmental conditions, and improved biochemical stability, making them particularly suitable for industrial wastewater treatment processes. *Pseudomonas* sp. SU-EBT intracellular laccase activity induction describes its role in the decolorization of Congo red (Telke, et al., 2010). The textile, pulp, paper, leather and dye manufacturing industries generate enormous volumes of coloured wastewater containing synthetic dyes with complex aromatic structures such as azo,

anthraquinone and triarylmethane chromophores. These structural characteristics render the dyes highly resistant to natural biodegradation and conventional wastewater treatment methods (Chen, 1989; Zollinger, 1991). It is estimated that approximately 10–15% of the dyes used during textile processing are released into industrial effluents, causing severe environmental contamination (Yu, 2004).

Conventional physicochemical treatment methods, including coagulation, adsorption, and chemical oxidation, are often expensive, energy-intensive and may generate secondary pollutants. In contrast, microbial and enzymatic degradation approaches offer environmentally benign, cost-effective and sustainable alternatives for the detoxification and mineralization of these hazardous compounds. For practical industrial applications, detailed characterization of biodegradative enzymes is essential to understand their catalytic mechanisms, substrate specificity, structural stability, and potential for immobilization, which can significantly enhance enzyme reusability and operational efficiency in continuous wastewater treatment systems (Velu et al., 2011).

Advances in computational biology have further enabled comprehensive structural and functional analyses of enzymes through *in silico* approaches, providing valuable insights into enzyme–substrate interactions prior to experimental validation. In this context, the present study aims to establish a comprehensive *in silico* computational framework for the structural characterization of laccase from *Pseudomonas putida*. The study focuses on predicting the three-dimensional structure of the enzyme, evaluating its physicochemical and structural properties, and investigating its molecular interactions with three commercially important synthetic dyes—Congo Red, Indigo, and Crystal Violet—using molecular docking approaches. The findings of this study are expected to enhance our understanding of the catalytic potential of *P. putida* laccase and provide a theoretical basis for the development

of efficient enzyme-based bioremediation strategies for the treatment of dye-contaminated industrial wastewater.

METHODOLOGY

Sequence retrieval

The primary amino acid FASTA sequence of the laccase enzyme from *Pseudomonas putida* was retrieved from the NCBI database with the reference accession number WP_016713391.1 (Bernstein et al, 1977). The sequence analysis indicated a length of 246 amino acids for the monomeric protein chain. The three-dimensional chemical structures of the target industrial dyes—namely Congo Red (PubChem CID: 6166), Crystal Violet (PubChem CID: 11057), and Indigo (PubChem CID: 5318597)—were retrieved from the PubChem compound database in SDF format (Wang et al, 2009). The laccase protein sequence was subsequently subjected to BLASTp analysis against the non-redundant protein database, from which 15 closely related homologous sequences were selected based on high query coverage and sequence identity for subsequent alignment (Altschul S.F. et al, 1990).

Multiple Sequence Analysis

The 15 homologous hits retrieved from the BLASTp results were aligned for multiple sequence analysis using the CLUSTALW algorithm within the MEGA software package (Tamura K et al, 2007; Larkin M.A. et al, 2007). Based on the multiple sequence alignment, a phylogenetic tree was reconstructed using the Neighbour-Joining (NJ) method. To address critical statistical reliability and ensure tree robustness, the phylogenetic tree was evaluated using 1000 bootstrap replicates, and the final sequence conservation, consensus regions, and evolutionary relationships were analysed and visualized using the Jal View workbench (Waterhouse A.M., et al, 2009).

Domain analysis and Motif searching

Domain analysis was performed using the Conserved Domain Architecture Retrieval Tool (CDART) at NCBI (Geer et al, 2002) to map the functional and putative domain architectures of the enzyme. To achieve higher sequence-level resolution of functional motifs,

structural motif searching was completed using the Motif-Scan server against the Pfam database profiles (Naughton B.T. et al 2006), ensuring precise identification of signature multicopper oxidase binding sites.

Homology Modelling

The three-dimensional structure of the *P. putida* laccase enzyme was predicted using the SWISS-MODEL workspace web server (Waterhouse, A., et al, 2018). The target FASTA sequence was modelled using the high-resolution crystal structure of the multi-copper oxidase from *Escherichia coli* (PDB ID: 1u05) as the primary structural template, which was chosen based on optimal Global Model Quality Estimation (GMQE) and QMEAN scoring parameters generated by the SWISS-MODEL pipeline for the target-template alignment (template PDB ID 1u05; the template-derived sequence identity, sequence coverage, template resolution, GMQE score, and QMEAN score for the selected model are reported in Table S1). While the target monomeric chain contains 246 residues, the functional template (1u05) exists as a homo-oligomer; hence, the target model was generated in its biological multimeric configuration to closely mirror native functional architectures, resulting in a total of 412 residues evaluated in the final structural coordinate file. The structural and stereochemical validity of the generated 3D coordinates was thoroughly evaluated using PROCHECK via the generation of a Ramachandran plot (Laskowski R.A., et al, 1993).

Molecular Docking studies

To investigate the geometric complementarity and specific non-covalent interactions between the *P. putida* laccase and the industrial dyes, molecular docking studies were conducted using the PATCHDOCK web server (Duhovny et al., 2002; Schneidman et al., 2005). Patch Dock utilizes a rigid-body shape complementarity algorithm to evaluate receptor-ligand fits. Because specific catalytic active-site residues for this novel bacterial laccase variant have not been previously mapped through *in vitro* experimental assays,

an unbiased blind docking approach was executed across the entire protein surface to comprehensively identify potential binding pockets. Default docking parameters were maintained. The resulting top-scoring docked complexes were subsequently processed for structural refinement and atomic contact energy (ACE) minimization using the Fire Dock algorithm, followed by final local model quality assessments using the QMEAN server functionalities (Benkert P. et al., 2009; Benkert P. et al., 2008).

RESULTS

Sequence retrieval and BLAST

The multi-copper polyphenol oxidoreductases from closely related *Pseudomonas* and Gamma proteobacteria species demonstrated the highest alignment scores and sequence identities, reaching up to 100% and 98%, respectively. Across all 15 selected homologous hits, the sequence identity remained remarkably high, decreasing to a minimum of 96% for the lowest hit, while consistently maintaining a 100% query coverage. This confirms a highly conserved evolutionary lineage for the laccase enzyme target within the genus *Pseudomonas*.

Multiple Sequence Alignment

Multiple sequence alignment performed using CLUSTALW via MEGA revealed significant structural conservation (Fig. 1). Visualization

through Jal View underscored high-density blocks of conserved domains, strict consensus segments, and high-quality alignment profiles. The reconstructed Neighbour-Joining phylogenetic tree highlighted clear evolutionary distances and branching lineages among the 15 sequences (Fig. 2). The high bootstrap value support confirms that the target sequence is highly homologous to established bacterial multi-copper oxidases.

Domain analysis and Motif searching

Domain characterization via CDART identified a signature multicopper oxidase architecture, showcasing relevant domain arrangements across related bacterial groups such as Enterobacteriaceae, Teredinibacter, and others (Fig. 3). Motif-Scan analysis successfully mapped a definitive 'Cu-oxidase_4' multi-copper polyphenol oxidoreductase laccase signature (under Pfams's: Cu-oxidase_4) spanning residues 34-243. This motif returned an exceptional raw score of 401.5, a normalized N-score of 128.673, and an E-value of 4.5e-122 (Fig. 4). Additionally, a minor Seven Residue Repeat (SRR) motif (pfam_fs: SRR) was detected between residues 167-176 with a raw score of 1.2 and an E-value of 1.6, confirming the biological annotation of the protein as a true laccase family member.

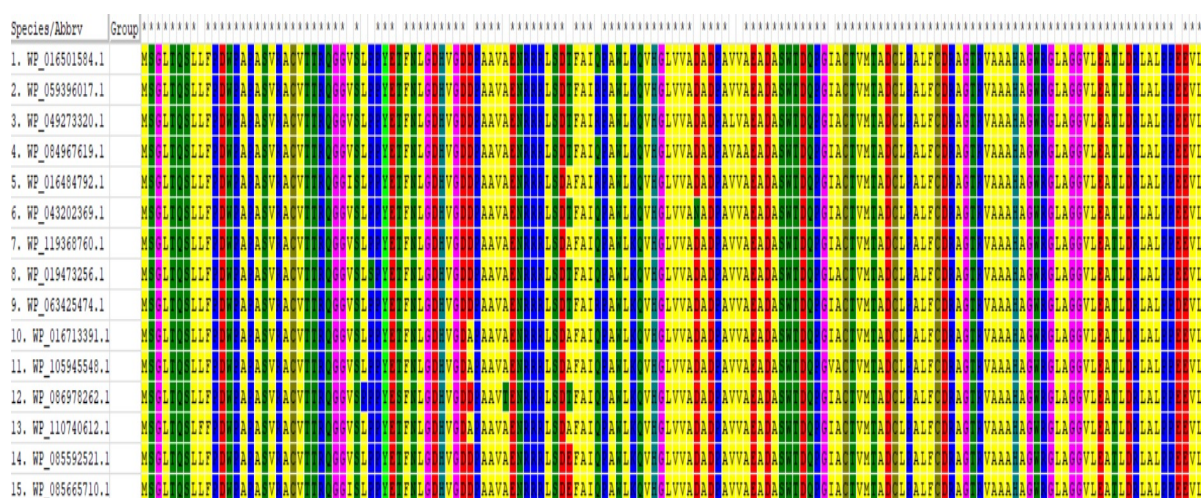


Figure 1: Showing the alignment of 15 sequences that were taken from the BLAST result page. All these sequences taken showed the highest of 100% identity and the lowest of 96% till the last sequence taken. The alignment is done in MEGA using the ClustalW alignment program. The sequences show a very good alignment with the query sequence.

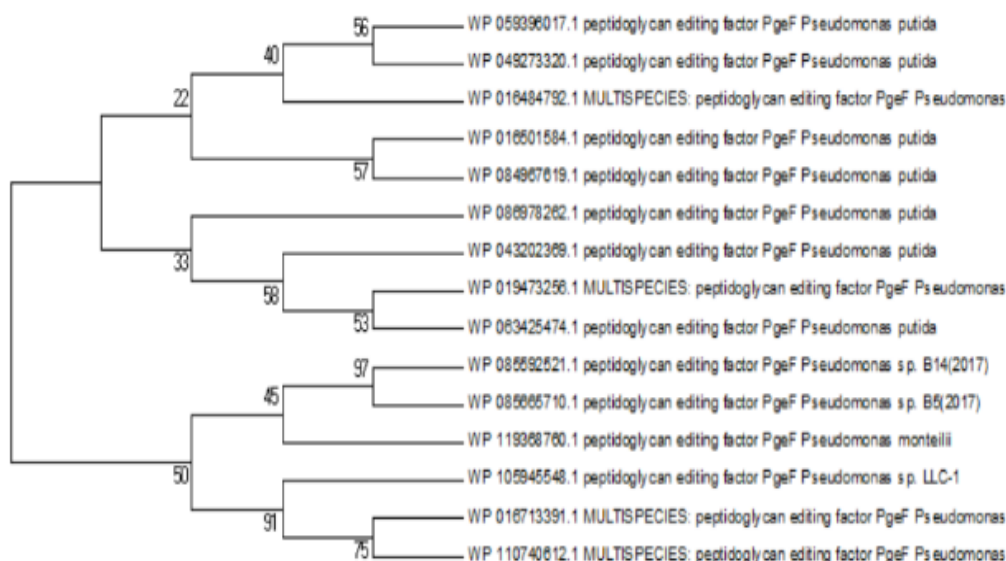


Figure2: Showing the Neighbour Joining Phylogenetic tree with 500 bootstrap replicates generated via MEGA and viewed in Jal View. The tree is also provided with the branch lengths in them. Since Neighbour Joining is considered accurate, the tree was constructed with that method and since only 15 sequences were taken, hence 500 bootstrap steps are enough.



Figure 3: Showing the domains present in the laccase enzyme from *P. putida*. CDART was utilized for generating the domains present in the enzyme. The query sequence was pasted, and the domains were shown as per the figure above

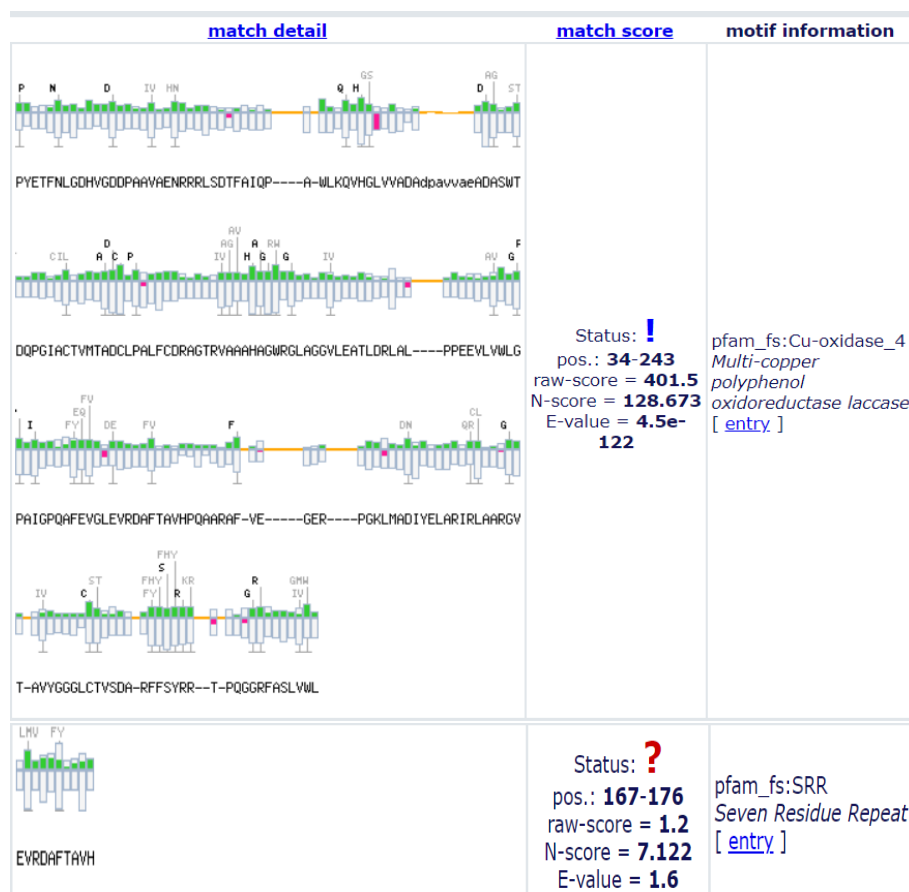


Figure 4 : Showing the motif scan analysis of laccase enzyme from *P. putida*. It also shows the raw score, N-Score and E-value also followed by the motif information

Homology Modelling

The 3D structural model of the laccase enzyme was successfully built using the SWISS-MODEL server based on the template multi-copper oxidase structure (PDB ID: 1u05) (Fig. 5). Stereochemical assessment via PROCHECK generated a detailed Ramachandran plot to evaluate backbone conformation stability. The statistics revealed that 80.1% of the residues (330 residues) were positioned inside the most favoured regions, 18.2% (75 residues) inside additional allowed regions, 1.0% (4 residues) inside generously allowed regions, and a minor 0.7% (3 residues) fell within disallowed regions, out of 412 total evaluated non-glycine and non-proline residues. While the presence of only 3 residues in the disallowed regions indicates a stable structural core, the percentage of residues inside the most favoured region (80.1%) is somewhat lower than the standard

90% benchmark typically expected for high-resolution experimental structures. This variation can be attributed to the loop flexibilities inherent to modelling a bacterial multimeric enzyme state. Consequently, this model serves as a reliable structural prototype for initial *in silico* target screening, though subsequent molecular dynamics (MD) simulations would be beneficial to refine local loop geometries and optimize regional backbone stability.

Molecular Docking studies

Rigid-body molecular docking via the PATCHDOCK server yielded valuable insights into the prospective binding configurations and surface shape complementarity between the laccase model and the three dyes (Table 1, Fig. 6). Among the evaluated ligands, Congo Red achieved the highest geometric complementarity docking score of 7434 with an

interacting surface area of 949.60 Å² and a favourable atomic contact energy (ACE) of -74.63 kcal/mol. Crystal Violet achieved an intermediate docking score of 5964 (Area: 678.80 Å², ACE: -129.79 kcal/mol), while Indigo displayed the lowest geometric score of 4112 (Area: 450.80 Å², ACE: -91.78 kcal/mol). Residue-level interaction analysis indicated that the Congo Red-laccase complex was uniquely stabilized by specific hydrogen bonding interactions, yielding a hydrogen bond fraction score of 0.2, involving proximal residues highlighted in the 2D interaction maps (Fig. 6b). In contrast, Crystal Violet and Indigo relied exclusively on non-bonded hydrophobic interactions and Van der Waals forces, exhibiting an absence of conventional hydrogen bonds (0.0). Decisively, it must be emphasized that Patch Dock scores reflect structural shape matching and pseudo-atomic contact energies rather than true thermodynamic free energy of binding (ΔG) or active-site chemical turnover rates. Furthermore, since a rigid-body blind docking approach was implemented, it does not simulate induced-fit conformational adjustments. Therefore, the prominent score for Congo Red confirms excellent geometric fit and

surface recognition but does not inherently establish a faster rate of catalytic biodegradation. These findings provide a compelling structural rationale for prospective binding affinity, which must be validated using experimental *in vitro* kinetic assays.

DISCUSSION

The present study establishes an integrated computational workflow to decipher how *Pseudomonas putida* laccase engages three industrially important dyes. Sequence retrieval and BLASTp analysis confirmed maximal identity with polyphenol oxidoreductases from *Pseudomonas* and Gamma proteobacteria species, and this identification was independently reinforced by multiple sequence alignment, CDART domain mapping, and Pfam motif scanning, which together confirmed the canonical multicopper oxidase architecture and the diagnostic Cu-oxidase_4 signature. This convergence across three independent bioinformatic approaches gives confidence that the modelled protein is a genuine laccase rather than a structurally related but non-catalytic oxidase, and it justified carrying the sequence forward into homology modelling and docking.

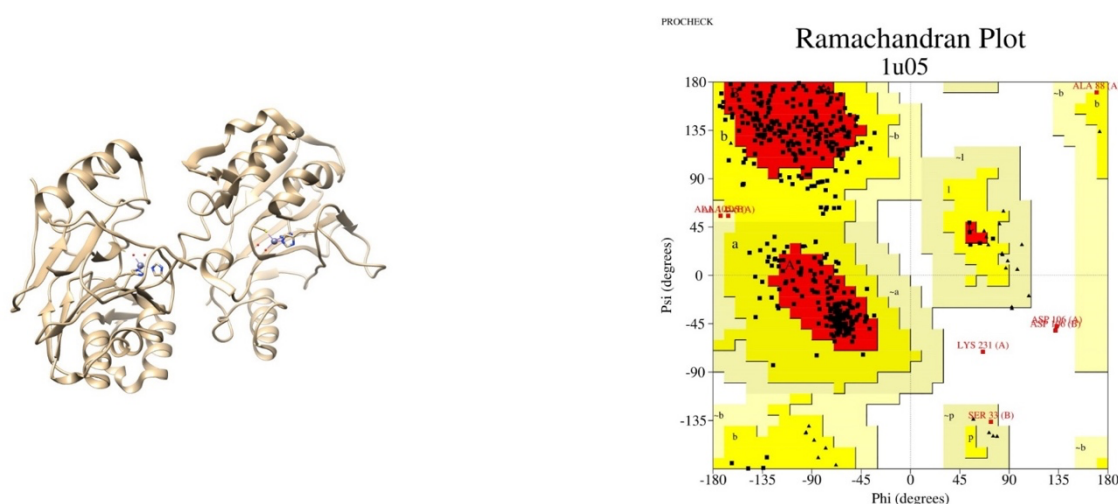


Figure 5: Showing the homology model of laccase enzyme from *P. putida* and its corresponding Ramachandran Plot from Pro Check server. Most favoured regions were found to have 330 residues with 80.1%, additional allowed regions with 75 residues with 18.2%, generously allowed regions with 4 residues with 1.0%, followed by the disallowed regions with 3 amino acid residues with 0.7% and non-Glycine and non-Proline residues with 412 residues

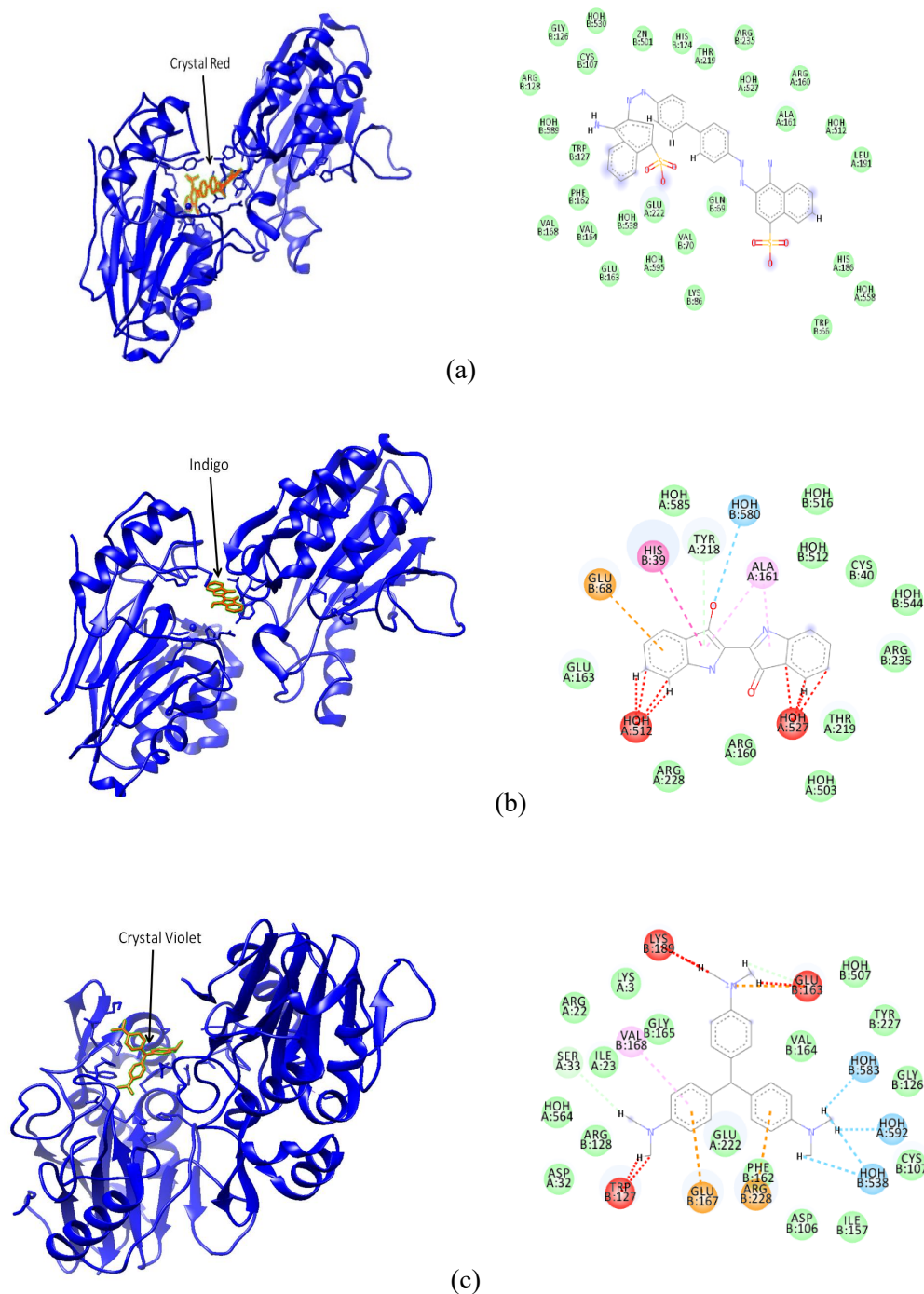


Figure 6: Showing the molecular interactions of (a) 1u05 and crystal red, (b) 1u05 and indigo and (c) 1u05 and crystal violet. The dyes (ligands) are marked in the above figures in orange red colour and the receptor is coloured in blue. The ligands are in ball and stick format. Also, the amino acid residues (with the chain of the enzyme they belong and positions) interacting with them are provided.

Table 1: Showing the molecular docking analysis of laccase as the receptor and the dyes as ligands. It includes the docking score, area covered and ACE (atomic contact energy) and Hydrogen Bonds (HB). The results were further processed via Fire Dock and then the values are provided.

Receptor	Ligands	Docking Score	Area	ACE	HB
(1u05)	Congo Red	7434	949.60	-274.63	0.2
	Indigo	4112	450.80	-91.78	0.0
	Crystal Violet	5964	678.80	-129.79	0.0

The homology model, built on the *Escherichia coli* multicopper oxidase template (PDB 1u05) in its biological multimeric configuration, showed an overall stable fold, with 80.1% of residues in the most favoured Ramachandran regions and only 0.7% in disallowed regions. This value sits below the approximately 90% benchmark generally expected of high-confidence structures, a shortfall that is not unusual for homology models of bacterial multicopper oxidases built without an exact-sequence experimental template; comparable models used directly for blind docking of dyes and other xenobiotics against bacterial and fungal laccases have reported similar loop-region deviations (Buzzo et al., 2023). Consequently, we consider explicit-solvent molecular dynamics refinement of the flexible loop regions – as has been used to stabilize analogous laccase-substrate models before docking (Bhatt et al., 2023), a necessary next step before this structure is used for active-site engineering rather than for the present exploratory screening. Interpreting the docking hierarchy considering dye chemistry, rather than as a simple activity ranking, is instructive. Congo Red is a large, bis-azo, desulphonated diamino biphenyl dye; its extended and comparatively flexible aromatic backbone and anionic sulfonate/amine substituents are consistent with the largest interacting surface area recorded here (949.6 Å²) and the only appreciable hydrogen-bond contribution among the three ligands (fraction 0.2). Sulfonated azo dyes have similarly been reported to form more extensive hydrogen-bonded contacts with surface loops of bacterial and fungal laccases in

comparable docking studies (Li et al., 2025). Crystal Violet, a delocalized cationic triarylmethane dye, engaged the modelled surface predominantly through hydrophobic and van der Waals contacts without conventional hydrogen bonding, a pattern also reported for triarylmethane dyes docked against laccases from other sources, which tend to associate through π -stacking with aromatic side chains rather than through polar contacts (Li et al., 2025). Indigo, the smallest and most rigid of the three ligands, occupied the least surface area and returned the lowest geometric score, which more plausibly reflects its limited number of solvent-accessible polar groups than any inherent resistance to enzymatic attack. It bears repeating, that Patch Dock and Fire Dock scores quantify geometric shape complementarity and pseudo-atomic contact energy rather than true binding free energy (ΔG), and they do not identify directly about the single-electron oxidation chemistry that occurs at the laccase type-1 copper centre during catalysis. Because no experimentally confirmed catalytic residues exist for this bacterial variant, docking here was necessarily performed in blind mode across the entire modelled surface; the resulting poses, however favourable, describe candidate surface-recognition events rather than confirmed, catalytically productive orientations relative to the copper cluster. Reviews of docking-based bioremediation studies draw the same distinction, noting that a favourable score can prioritize candidates for downstream testing but cannot, on its own, establish degradation efficiency (Iniguez-Luna et al., 2025). The present ranking – Congo Red greater than

Crystal Violet greater than Indigo – should therefore be read as a structural hypothesis about relative surface affinity to be tested against real decolorization and degradation data, not as a confirmed biodegradation order. This caveat does not diminish the practical relevance of the findings. Bacterial laccases have repeatedly been shown, once immobilized or otherwise stabilized for continuous operation, to decolorize structurally diverse azo, anthraquinone, and triarylmethane dyes in wet-laboratory systems; immobilization strategies such as alginate encapsulation, nanoparticle conjugation, and vault-nanocage packaging have each been used to improve laccase stability and reusability for dye-wastewater treatment (Velu et al., 2011; Gao et al., 2022; Thathola et al., 2024; Chauhan & Choudhury, 2021). The present structural model and its residue-level contact maps therefore provide a rational starting point for prioritizing Congo Red for early wet-lab or immobilization-based follow-up, while parallel assays would still be required to establish whether the weaker, purely hydrophobic docking profiles of Crystal Violet and Indigo translate into meaningfully lower degradation rates in practice. Taken together, three concrete next steps (i) explicit-solvent molecular dynamics refinement of the homology model to resolve the loop regions responsible for the sub-90% Ramachandran score; (ii) active-site-directed rather than purely blind docking once mutagenesis or structural data localize the catalytic type-1 copper pocket, ideally using flexible-ligand or induced-fit protocols capable of capturing conformational adjustment on binding; and (iii) *in vitro* validation through UV-visible decolorization assays, HPLC/LC-MS degradation-product profiling, and enzyme kinetic measurements, following experimental designs used for other bacterial laccase-dye systems (Dai et al., 2021; Li et al., 2025). Only this combined computational-experimental evidence can convert the present structural ranking into a validated statement about which dye *Pseudomonas putida* laccase degrades most efficiently.

CONCLUSION

In summary, this is a bioinformatics-driven approach to characterize the Laccase enzyme from *P. putida* and evaluate its potential for dye degradation. Through sequence analysis and homology modelling, the enzyme's structure was validated as stable and functional, specifically showing a high density of conserved domains that are essential for the catalytic activity of these enzymes.

The *in silico* docking results highlight that while the enzyme interacts with multiple dyes, its geometric and hydrogen-bonding complementarity with Congo red is the strongest among the three dyes tested, a structural finding that is suggestive of, but does not by itself confirm, superior degradation potential for this pollutant; this hypothesis would need to be evidenced through molecular dynamics refinement and *in vitro* kinetic and decolorization assays. These findings support the further investigation of *P. putida* laccase particularly in the sustainable treatment of industrial effluents.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

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Fecal microbiota transplantation as a curative strategy during intestinal and neurological disorders

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ABSTRACT

The symbiotic gut microbiota is essential for optimal physiology. The gut microbiota composition and diversity may significantly alter leading to dysbiosis which may give rise to various pathologies in the host. Dysbiosis is correlated to metabolic syndrome, neurodegenerative disorders, gastrointestinal tract (GIT) complications, liver disease amongst many others. Fecal microbiota transplantation (FMT) is an effective strategy to introduce feces (containing normal microbial population) from a healthy donor into the gut of a compromised recipient. Originally, FMT was introduced to mainly treat gastrointestinal complications caused by pathogenic microbes. However, over the years FMT has gained popularity as a treatment regimen for relief during GIT and nervous system disorders. Initial findings from FMT studies are positive and promising in rodents and clinical trials. However, clinical applicability of FMT is currently limited due to its practical dissent in treating diseases. Moreover, FMT had little success in treating some conditions which could be due to variations in FMT strategy and patient factors. In this article, new reports resulting from FMT shall be reviewed with respect to a few intestinal and brain diseases.

KEYWORDS: Dysbiosis; Feces; Gut microbiota; Gastrointestinal; Inflammation; Metabolites

INTRODUCTION

The human gut is host to innumerable complexity and number of microorganisms called the microbiota that exhibit commensal and/or symbiotic relationship with the host. The gut microbiota is composed of bacteria, fungi, archaea, parasites, viruses and bacteriophages whose number for seeded the host total body cell counts (Thursby and Juge, 2017; Adak A and Khan, 2019). The gut microbiota constitutively interacts with the intestinal tract. Such interaction is essential to maintain optimal host physiological roles that provide immune sensing and antigenic tolerance including development of immunocytes (Shapiro et al., 2014; Rooks and Garrett, 2016; Illiano et al., 2020). The interplay also restrains pathogen colonization and propagation benefitting the host. Optimal gut microbial composition and

diversity is essential in maintaining commensal/symbiotic ¹relationship (Kataoka, 2016). However, the gut microbial community may undergo shifts due to several factors that may alter its diversity (Karl et al., 2017; Mitrea et al., 2022). Exogenous factors include diet, therapeutic drugs, alcohol etc., whereas the endogenous factors comprise age, disease state, sex, genetics, host mucosa and immunity etc. (Karl et al., 2017; Bibbò et al., 2016; Gomaa, 2020; Nikolova et al., 2021). Gut dysbiosis in the host may trigger pathological outcomes ranging from metabolic disorders, inflammation to neuropsychiatric complications (Nikolova et al., 2021; Boulangé et al., 2016). Therapeutic interventions in treating such disorders are limited due to its inherent intractability. Gut microbial manipulations can be an approach especially in

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gut diseases such as inflammatory bowel disease (IBD) (Weingarden and Vaughn, 2017). Fecal microbiota transplantation (FMT) is a tried and tested strategy whereby normal fecal microbiota (from the feces) of a healthy donor is transferred to the diseased recipient's intestine. FMT has proven successful towards recurring *Clostridium difficile* infection and might be effective against IBD (Weingarden and Vaughn, 2017; Song and Kim, 2019). FMT has the potential to treat gastrointestinal diseases, cancer, autoimmune diseases, obesity, and metabolic syndrome.

Obesity has been demonstrated to have a link with dysbiosis. Obese mice show a relatively higher proportion of Firmicutes as against Bacteroidetes when compared to lean animals with similar findings in humans (Pedersen et al., 2013; Hansen et al., 2014; Walters et al., 2014). Interestingly, FMT from obese to the germ-free mice led to obesity onset (Turnbaugh et al., 2008; Backhed et al., 2007). Also, FMT from non-obese mice to obese led to dramatic improvement and shift to a lean status (Vrieze et al., 2020). The use of pro/prebiotics however has provided relief only in certain GIT complications. Currently, FMT is seen as a useful intervention in GIT and neurological disorders, especially those linked to the intestinal microbiome.

Fecal microbiota transplantation

The gut microbiome maintain communication with various tissues and organs exploiting the various microbial-derived metabolites and the vagus nerve (Pluznick et al., 2013). Many gut-microbial metabolites (tryptophan/indole metabolites, short-chain fatty acids, secondary bile acids, branched chain amino acids etc.) act by adjusting the hormonal and immune signaling pathways in the host (Table 1) (Maynard et al., 2012; El Aidy et al., 2015). Moreover, these metabolites stimulate the parasympathetic nervous system playing a crucial role in homeostasis through metabolic regulation (De Vadder et al., 2014). Furthermore, by modulating the gut-brain axis (GBA), microbial metabolites can profoundly influence the brain (Rhee et al., 2009). A

dysbiotic gut may trigger metabolic disorders including neurological and neuropsychiatric complications. Gut dysbiosis may return to a normal state with interventions such as administration of specific antibiotic against pathogenic strains or probiotics or FMT (Deidda et al., 2021). However, use of antibiotics has limitations such as development of microbial resistance and off-target actions (Gorski et al., 2016). Probiotic supplements though beneficial in GIT complications, however it provides only a limited bacterial species and strains (Deidda et al., 2021; Dimidi et al., 2017). FMT is an alternative, physiologically relevant strategy tried to provide relief from certain human diseases linked to dysbiosis.

In FMT, feces containing active microbiota belonging to a healthy, disease-free donor is transferred to a subject with a disease linked to dysbiosis for therapeutic purpose (Ramai et al., 2013; Rossen et al., 2015; Vendrik et al., 2020). FMT has advantages as it transfers the entire pool of microbes safely and does not provoke immune response (Rossen et al., 2015). The donor fecal matter needs to be properly processed before transfer to the individuals (Kao et al., 2017; Haifer et al., 2022; Allegretti et al., 2020; Bajaj et al., 2019). Processed fecal matter can be administered to subjects by delivery methods broadly classified into upper (such as oral capsules) and lower gastrointestinal routes (by colonoscopy). However, clinical applicability of FMT is limited due to its practical dissent in treating diseases.

FMT and human diseases

FMT has been tried and tested in humans as a therapeutic regimen for several illnesses. However, the efficacy of FMT in treating certain human diseases is still in its infancy. Appropriate literature search and selection were carried out using various keywords in public databases such as PubMed (NLM, NIH, USA) and google scholar. The following diseases have been reviewed in detail owing to numerous data that underscores dysbiosis as a

reason for their possible cause, progression and maintenance in the gut and the brain.

In irritable bowel syndrome

Irritable bowel syndrome (IBS) is a complex, less understood and chronic condition characterized by a group of symptoms that largely results from abnormal gut motility. Abdominal pain, diarrhoea and/or constipation, weight loss, anxiety and depression are typical symptoms, with 4-10% of people worldwide suffer from it (Ford et al., 2020). The etiology of IBS is unknown, and no single treatment is enough to provide relief. Physicians recommend changes in diet and lifestyle, medicines, probiotics supplement as interventions on an individual basis (Vasant et al., 2021; Masuy et al., 2020). IBS is generally characterized as IBS-D (diarrhoea-predominant), IBS-C (constipation-predominant) and IBS-M (mixed) subtypes. The gut microbiota composition and diversity of IBS subjects are different from the healthy ones indicating its role in IBS pathophysiology (Ohman and Simren, 2013). Modulation of gut microbiota may provide relief from IBS. FMT from healthy donors to IBS patients has been attempted in previous two studies (Johnsen et al., 2018; Halkjær et al., 2018).

Findings from one of those studies revealed decline of IBS symptoms, whilst the other found no effect. However, in a recent study of 165 patients with IBS to placebo (own faeces), 30 g FMT or 60 g FMT at a ratio of 1:1:1 was conducted (Holster et al., 2021). Results obtained showed significant decrease in IBS symptoms such as fatigue and improvement in physical health at three months after the introduction of FMT. Gut bacterial profiles in the group receiving FMT exhibited significant changes. Furthermore, the response to FMT increases with the fecal dose (Holster et al., 2021). FMT in the form of capsules were ineffective, rather colonoscopy and gastroscopy were successful in alleviating IBS symptom in patients. Allogenic FMT (faecal material from a healthy donor) is more potent compared to autologous FMT (own fecal matter).

Allogenic FMT altered the gut microbiota composition in patients and was detectable for 6 months, whereas no such observation was made by autologous FMT (El-Salhy et al., 2020). Allogenic FMT including autologous FMT however made no impact on the fecal metabolites measured. However, correlations between the gut microbial composition and secreted metabolites showed that the microbe-metabolite interactions get disrupted after allogenic FMT compared to autologous FMT. In another finding, however, FMT was ineffective in providing relief from IBS symptoms in randomized-controlled trials (RCTs) which could be due to variations in FMT strategy and patient factors (Myneedu et al., 2019). In one more RCTs, FMT relieved IBS symptoms as compared to placebo (autologous transplant). However, the positive effects declined after one year and a second FMT restored the effects to previous level in patients (Holvoet et al., 2021).

Additional RCT findings showed no differences in sex-related FMT response in IBS patients and in placebo (El-Salhy et al., 2021). However, the response rate (reduction in symptoms) was higher in female patients compared to males in IBS-D case at one month and three months after FMT. A 5-year effect was reported in a retrospective analysis (Hillestad et al., 2022). In the study, patients with all subtypes of IBS received FMT through nasojejunal administration, colonoscopy administration, or freeze-dried capsules from healthy donors. 50% of the patients showed improvement in symptoms after one month and 70% and 75% after one and two years, respectively. Also, after five years, 60% of patients showed improvement. These results point that repeated FMT might be required towards sustained relief from IBS symptoms and improve the quality of patient's life. In yet another investigation, double-blind, randomised, placebo-controlled patients aged 18-65 years with IBS-D were observed (Aroniadis et al., 2019). The subjects received either 75 FMT capsules or 75 placebo capsules over 3 days (25 capsules per day).

All the patients went to the alternate treatment at 12 weeks. Findings from the study indicate no significant relief from IBS symptoms because of FMT in patients compared to placebo. In a double-blind randomized placebo-controlled, parallel-group, single-centre study patients with non-constipated IBS were investigated (Johnsen et al., 2020). FMT was able to trigger significant relief from fatigue and improved the quality of life in the IBS patients compared to the placebo group. The administration route (colonoscopy or gastroscopy) of FMT is vital to get effective response and improve the quality of life in patients. Long-term effect of FMT during IBS is unknown and would be an interesting area for future research.

In inflammatory bowel disease

Inflammatory bowel disease (IBD) comprises of Crohn's disease, CD and ulcerative colitis, UC) that affects the gastrointestinal tract (GIT). It is associated with chronic inflammation of the GIT leading to persistent diarrhoea, weight loss, fatigue, abdominal pain and rectal bleeding in sufferers (Ananthakrishnan et al., 2018). The etiology of IBD is unknown but is attributed to attenuated host immune responses. Altered immune response to environmental triggers, such as microorganisms including viruses (Ananthakrishnan et al., 2018; Lee et al., 2018; Canakis and Qazi, 2020) may drive IBD. Secondly, individual genetic predisposition also might be the driver of IBD (Younis et al, 2020). In a recent study by Zhang et al, mice with experimental UC when subjected to FMT displayed higher body mass and gut weight and length (Zhang et al., 2020). There was a marked decrease in histopathological changes and cytokine expression in the gut accompanied with down-regulation of genes involved in pro-inflammatory mediator NF- κ B signalling were observed compared to control animals. FMT increased the relative population of Firmicutes and reducing the abundances of Bacteroidetes and Proteobacteria. FMT treated mice showed higher counts of *Lactobacillus*, *Butyric coccus* along with a fall in the population

of *Helicobacter*, *Bacteroides* and *Clostridium* (Zhang et al., 2020). Moreover, FMT increased the availability of anti-inflammatory SCFAs in the colon. These observations points to the beneficial role of FMT in alleviating UC in mice model. Gut bacteria have a prominent role in CD onset and progression and hence FMT might be useful as a therapeutic strategy. In fact, in a randomized, single-blind pilot trial of FMT, significant remission was reported from CD with decrease in CRP level (Sokol et al., 2020). Also, elevated dose of fecal matter led to beneficial effect and help sustain the remission state. The importance of FMT is further supported by antibiotic administration in murine models. Separate antibiotic pre-treatment with vancomycin, metronidazole and streptomycin of murine fecal donors before FMT to colitic animals gave interesting results. Gut microbiota and fecal metabolome analyses of the FMT-recipient animals showed reduced ability of FMT to control intestinal inflammation (Strati et al., 2021). Both vancomycin and streptomycin treatment, but not metronidazole led to the inability of FMT to attenuate recipient intestinal inflammation. Also, pathobiont growth with increased presence of oxidative microbial-secreted metabolites in the gut was akin to what was observed during IBD (Strati et al., 2021). Characterization of the beneficial gut microbiota remains an enigma. In a double-blind clinical study by Paramsothy et al on UC, FMT increased the diversity and altered the composition of microbial population in the recipient fecal and colon samples (Paramsothy et al., 2019). Patients with UC remission after FMT exhibited increased counts of *Eubacterium. hallii* and *Roseburia inulivorans* as compared to control. Also, microbial generation of SCFAs and secondary bile acids were observed in the FMT recipient fecal and colon samples. Additionally, patients without remission from FMT were associated with enhanced *Fusobacterium gonidiaformans*, *Sutterellawads worthensis*, and *Escherichia* species counts with high levels of lipopolysaccharide (LPS) and heme synthesis

(Paramsothy et al., 2019). Metagenomic investigations in the donor fecal sample and recipient FMT have identified *Odoribacter splanchnicus* as a key microbial mediator in providing relief from intestinal inflammation during UC (Lima et al., 2022). *O. splanchnicus* present in the recipient FMT sample enhanced the Foxp3⁺/RORγt⁺ regulatory T cells and induced the expression of interleukin IL-10, and generation of SCFAs thereby providing significant relief from colitis in mice. In an interesting finding, FMT from IBD sufferer plus depression (IBD/D⁺) to recipient mice induces altered immune response with IBD-like colitis by increasing the myeloperoxidase activity and expression of pro-inflammatory mediators such as IL-1β and IL-6 in the colon (Jang et al., 2021). Also, FMTs from patients afflicted with IBD/D⁺ led to anxiety-/depression-like behaviours and accompanied with decrease in hippocampal BDNF⁺/NeuN⁺ cell number. Moreover, FMT from healthy volunteer into mice previously transplanted with IBD/D⁺-feces attenuated depression-/anxiety-like behaviours, hippocampal NF-κB⁺/Iba1⁺ and LPS⁺/Iba1⁺ cell counts associated with low circulating and fecal levels of LPS and colonic IL-1β (Jang et al., 2021). CD is a chronic condition exhibiting sustained inflammation and irritation of the digestive tract accompanied with dysbiosis. Symptoms of CD include abdominal pain, diarrhoea, rectal-bleeding and weight loss. Although the etiology of CD is unknown, several factors increase the risk of getting the disease such as autoimmune disease, host genetics and smoking. In a randomized study, FMT was performed in a group of patients (n = 27) with CD by gastroscopy and colonoscopy (Yang et al., 2020). A second FMT was performed after one week. Most patients (n = 18) with CD showed significant clinical remission (66%) from FMT. No difference was observed between gastroscopy and colonoscopy as the mode of fecal delivery. However, FMT recipients exhibited lower microbiota diversity in relation to the donors.

Moreover, recipients with second FMT after one week exhibited increased intestinal microbiota richness, with elevated populations of *Clostridium*, *Cronobacter*, *Fusobacterium*, and *Streptococcus* and reduced counts of *Bacteroides*, *Eubacterium*, *Faecalibacterium*, and *Roseburia* (Yang et al., 2020). Overall, the results from clinical studies on FMT towards IBD remission were favourable. However, there is an excessive degree of inconsistency in responses even amongst the recipients undergoing identical treatment protocol. FMT as a successful therapeutic strategy in IBD is however difficult to demonstrate. A major constraint of FMT during IBD is to maintain remission state in the recipients. Therefore, FMT at present is less of a treatment strategy and more of an intervention in IBD clinical trials and requires further refinements and normalization as a therapeutic strategy in the future.

In constipation

Constipation is a common condition characterized by a state whereby a person develops infrequent bowel motion with firm and dry feces. Constipation generally occurs due to slow gut contractions associated with increased reabsorption of water, resulting in dry and solid stool. Constipation can arise from medications, minimal dietary fibre, IBS, low water intake, intestinal complications and various other factors. Impaired gut motility is correlated with systemic inflammation and dysbiosis. FMT has been reported as effective in treating constipation by remodelling the gut microbiota and correcting dysbiosis. In a new clinical finding, individuals receiving FMT showed rise in bacterial populations of *Clostridiales*, *Fusicateni bacter* and *Paraprevotella* with significant relief from symptoms as compared to pre-FMT state (Zhang et al., 2021). On the other hand, however, gut bacteria including *Lachnoan aerobaculum* underwent reduction in counts, which might correlate with the severity of patients' constipation.

The levels of SCFAs were comparable between pre-and post-FMT. The pro-inflammatory

cytokine IL-8 level was however reduced in FMT recipients, but the others such as IL-4, IL-6, IL-10 and IL-12p70 remain unaltered (Zhang et al., 2021). Hence, FMT can regulate gut microbiota ecology and cytokine levels thereby influencing systemic inflammation in constipated individuals. In another study, eight patients underwent three exposures to FMT (Xie et al., 2021). Clinical remission in the recipients up to 75% was achieved after the third exposure. Additionally, 16S rRNA sequence show decreased population of *Bacteroidetes* and *Firmicutes* with associated increase in *Actinobacteria* (*Bifidobacterium*), *Proteobacteria* (*Escherichia*), and *Firmicute* (*Lactobacillus*) numbers after FMT (Xie et al., 2021). Metabolomic and biochemical analyses showed that the fecal samples of FMT-exposed patients exhibited relatively elevated levels of N-Acetyl-L-glutamate, gamma-L-glutamyl-L-glutamic acid and Glycero phosphocholine. Increased circulatory levels of L-Arginine, L-Threonine, Ser-Arg, Indole acrylic acid, Phe-Tyr, 5-L-Glutamyl-L-alanine was also detected in the FMT recipients.

These changes in the gut microbial metabolome of FMT recipients were accompanied with significant relief in STC symptoms. In another chronic functional constipation (CFC) study, thirty-four patients with FMT exhibited a clinical cure rate of 73.5% (25/34) followed by a remission rate of 14.7% (Tian et al., 2020). FMT induced intestinal peristalsis and motility and raised the levels of circulating nitric oxide and serotonin. The sequencing of 16S rRNA from the FMT gut microbiome showed increased counts of *Bacteroides*, *Klebsiella*, *Megamonas*, *Erysipelotrichaceae* and *Epulopiscium* which might be the cause of CFC (Tian et al., 2020). On the other hand, high prevalence of *Prevotella*, *Acidaminococcus* and *Butyrivimonas* might be the reason for relief from CFC in FMT patients. Altogether, these findings suggest a role of FMT in improving gut microbiota ecology and metabolomic profile which could be beneficial in abating constipation.

In neurological disorders

The gut-brain axis (GBA) has been visualized as one of the primary routes whereby the brain communicates with the gut and vice-versa. The GBA involving the enteric nervous system (ENS) and CNS is critical for homeostatic regulation (Mayer, 2011). Over the years, the gut microbiome is seen as modulator of the GBA giving rise to the concept of microbiota-GBA (Rhee et al., 2009; Collins et al., 2012; Cryan et al., 2019; Cryan and Dinan, 2012). The gut microbiota-GBA is being considered as a vital modulator of the ENS and the CNS (Browning and Travagli, 2019). Gut dysbiosis may trigger alteration in microbiota-GBA inducing the onset and progression of some neurological disorders (Rao and Gershon, 2016; Margolis et al., 2021). Correction of dysbiosis by FMT might treat/cure dysbiosis-related neurological complications. Preliminary data indicate neurological disorders can be effectively managed by FMT, though few findings say the opposite. Parkinson's disease (PD) subjects typically show gut dysbiosis, however the link is unclear. FMT from PD mice model induced motor defects and striatal neurotransmitter decrease in healthy mice (Sun et al., 2018).

The population of *Firmicutes* and *Clostridiales* decreased, whilst an increase in *Proteobacteria* counts in fecal samples of PD mice with high fecal SCFAs level was observed. On the other hand, FMT reduced dysbiosis and fecal SCFAs level as well as physical impairment, and upregulated serotonin level in PD mice model. These findings show that dysbiosis might be participating in PD and that FMT can provide significant relief to PD mice by attenuating the TLR4/TNF- α signalling and neuroinflammation. In a similar finding, Zhao et al. reported gastrointestinal function impairment and altered behavioural performances in rotenone-induced PD mice model (Zhao et al., 2021).

However, FMT restored the gut bacteria composition and diversity and ameliorated gastrointestinal malfunctions and motor deficits in PD mice. FMT also decreased the levels of systemic inflammation in PD mice.

Additionally, FMT treatment curtailed neuroinflammation in substantia nigra of the brain and lowered damage to dopaminergic neurons (Zhao et al., 2021). FMT treatment to PD mice also reduced gut and circulatory LPS levels, including the substantia nigra by attenuating the TLR4/MyD88/NF- κ B signalling. Alzheimer's disease (AD) is the most prevalent form of dementia in senescent population exhibiting cognitive and memory decline. Clinically AD is an arduous to treat condition.

Although the etiology of AD is unknown, deposition of amyloid- β (A β) and tau-protein is a clinical feature in the patient's brain. The gut microbiota of AD patients and AD mice models differ in composition compared to healthy controls. FMT treatment improved the cognitive deficits and decreased the brain deposition of A β in APP^{swe}/PS1^{dE9} transgenic (Tg) mice (Sun et al., 2019). Also, decreased phosphorylation of tau protein and the levels of A β 40 and A β 42 appeared in Tg mice. Further, synaptic plasticity was elevated in Tg mice with reduced expression of COX-2 gene and high fecal SCFAs level. These findings could be the effect of FMT which reversed the gut microbial composition (Sun et al., 2019). In another report, FMT from 5xFAD mice into normal C57BL/6 mice (5xFAD-FMT) reduced adult hippocampal neurogenesis and brain-derived neurotrophic factor (BDNF) expression with high p21 expression contributing to memory impairment (Kim et al., 2021). Also, elevated levels of gut TNF- α and interleukin-1 β and in circulation were detected in 5xFAD-FMT mice. Composition of the 5xFAD-FMT mice gut microbiota showed differences compared control mice or wild type-FMT mice. Therefore, 5xFAD mice harboured a dysbiotic state that reduced neuronal generation by inducing colonic inflammation thereby aiding memory decline. Depression is a complex, less-understood neuropsychiatric condition with extensive morbidity. Recent findings have reported gut microbiota compositional differences in humans and rodent models with depression.

Altered brain chemistry was observed in patients and rodents with depression. Rat models exhibiting depression (CUMS), when subjected to FMT (CUMS+FMT) displayed improved symptoms of depression and colonic movements (Cai et al., 2022). Levels of serotonin, GABA and BDNF raised in the hippocampus of CUMS+FMT compared to the CUMS group. Also, GLP-1, IL-6 and LPS showed reduction in CUMS+FMT compared to CUMS. Also, CUMS group exhibited increase of glucagon-like peptide-1 (GLP-1), IL-6 and LPS and decrease of serotonin, GABA and BDNF when compared with the control (no depression) (Cai et al., 2022). The gut microbial richness of the CUMS+FMT group exhibit similarity to the control, whereas the richness decreased in the CUMS group. FMT was able to induce antidepressant effects on CUMS-induced depression involving a range of biochemical entities such as neurotransmitters, anti-inflammatory factors, neurotrophic factors and GLPs. Using an antibiotic cocktail, the gut microbiota of mice was depleted and then subjected to FMT colonization from normal mice or CUMS exposed mice (CUMS donors). Mice with CUMS and those with FMT from the CUMS donor exhibit higher anxiety- and depression-like behaviour when compared to the healthy controls (Li et al., 2019). Low abundance of gut *Lactobacillus* and increased richness of *Akkermansia* in the CUMS donor and recipient compared to control were observed. Hippocampal expression of Proinflammatory TNF- α and interferon- γ were upregulated in the CUMS mice group as against the control (Li et al., 2019). Dysbiosis impairs immunity and metabolic network which stimulate proinflammatory signalling pathways in the hippocampus via the GBA thereby inducing anxiety- and depression-like traits in mice.

Autism spectrum disorder (ASD) is a developmental complication due to discrepancies in the brain. ASD in some have a genetic component, whereas other causes are unknown. ASD subjects repeatedly exhibit anxiety, depression or attention-deficit

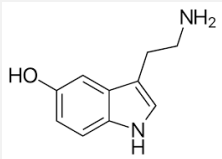
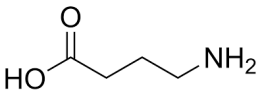
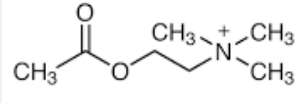
hyperactivity disorder (ADHD). In a clinical study by Kang et al, ASD children's fecal and plasma samples were analysed after undergoing FMT (Kang et al., 2020). ASD group metabolomic profiling revealed altered levels of plasma metabolites compared to the healthy children. FMT had a widespread effect in recipients, causing changes in circulating metabolites. Plasma metabolites (such as nicotinamide riboside, IMP, iminodiacetate, methyl succinate, galactonate, valyl glycine, sarcosine, and leucyl glycine) were decreased in the ASD group. (Kang et al., 2020). Metabolites like caprylate and heptanoate were however elevated in the ASD group. The plasma and fecal concentrations of these metabolites in the FMT recipients (with ASD) were modulated and attained levels typically observed in healthy children. Metabolic profiling study exhibited modulation of metabolites by the gut microbiome which is a key route to influence the GBA and could serve as biomarkers in treating ASD. By reestablishing gut microbial population through FMT from healthy subjects/animals to normal

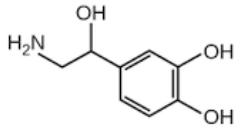
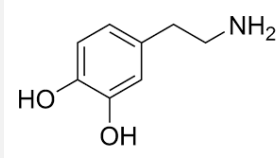
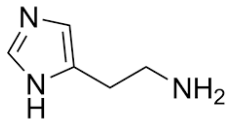
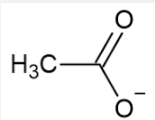
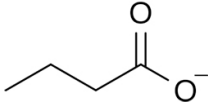
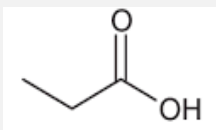
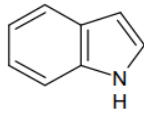
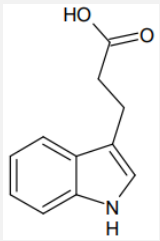
compositions ASD subjects can reverse various phenotypes associated with neurological impairments. It appears from several pre-clinical and clinical findings that FMT is a potent intervention for transmission and treatment of neurological complications.

Challenges and prospects

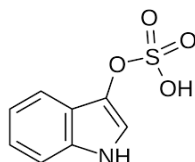
Over the years FMT has received encouraging support and popularity as a treatment intervention towards several GIT and nervous system disorders. Several pre-clinical and clinical findings show FMT as intervention for the treatment of intestinal and neurological disorders. At present, FMT is seen as a useful strategy in treating GIT and neurological disorders, especially those linked to the intestinal microbiome. However, clinical applicability of FMT is limited due to its practical dissent in treating diseases. A key hurdle is the isolation and characterization of key gut microbes responsible for the synthesis of host-modulating metabolites. Future studies on large randomized-controlled trials in a population are required to understand FMT in human diseases related to gut dysbiosis.

Table 1. Select gut microbial-derived metabolites secreted in the host intestine.

Metabolites	Chemical structure	Remarks	References
Serotonin		Regulates mood, memory, learning, cognition etc.	Boulangé et al, 2016; Collins et al, 2012
Gamma amino butyric acid (GABA)		Can reduce neuronal excitability by inhibiting nerve transmission. Can affect sleep.	Ananthakrishnan et al, 2018; Boulangé et al, 2016
Acetylcholine		Regulates attention, learning, arousal, involuntary muscle movement etc.	Canakis et al, 2020; De Vadder et al, 2014

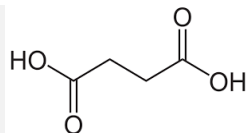
Norepinephrine		A vasoconstrictor increases heart rate and cardiac output. Can function both as a hormone and a neurotransmitter.	Deidda & Biazzo, 2021; El Aidy et al, 2015
Dopamine		Regulates mood, attention, memory, movement etc.	El-Salhy et al, 2020; Gomaa, 2020
Histamine		Can modulate the gut immune function and intestinal inflammation.	Halkjær et al, 2018; Shapiro et al, 2014
Acetate		Directly interact with host nuclear histone deacetylase causing gene expression reprogramming (epigenetic modification). Stimulates ghrelin secretion and control sleep and appetite.	Vendrik et al, 2020; Sokol et al, 2020
Butyrate		Participates in epigenetic modification. Stimulates leptin secretion and control sleep and appetite.	Mayer et al, 2011; Lima et al, 2020
Propionate		Participates in epigenetic modification. Stimulates leptin secretion and control sleep and appetite.	Lee et al, 2018; Kataoka, 2016
Indole		Weak aryl hydrocarbon receptor (AhR) agonist with anti-inflammatory and insulin sensitivity actions. Stimulate GLP-1 secretion.	Illiano et al, 2020; Holster et al, 2021
Indole 3-propionic acid (IPA)		Pregnane X receptor (PXR) agonist with anti-inflammatory effects and insulin sensitivity actions.	Haifer et al, 2022; El-Salhy et al, 2020

Indoxyl sulfate



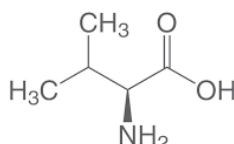
Contribute towards anxiety, depression, kidney disease etc. Dimidi et al, 2017; Collins et al, 2012

Succinate



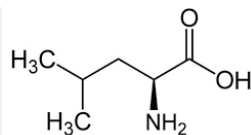
Enhances insulin sensitivity and glucose tolerance Browning et al, 2019; Myneedu et al, 2019

L-Valine



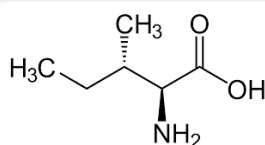
Roles in regulating protein, lipid and glucose metabolism, BAT thermogenesis & insulin resistance. Nikolova et al, 2021; Pluznick et al, 2013

L-Leucine



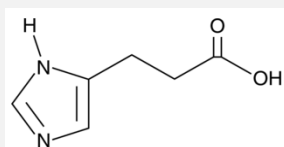
Roles in regulating protein, lipid and glucose metabolism, BAT thermogenesis, insulin resistance. Rhee et al, 2009; Strati et al, 2021

L-Isoleucine



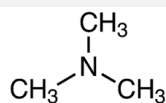
Roles in regulating protein, lipid and glucose metabolism, BAT thermogenesis, insulin resistance. Rhee et al, 2009; Strati et al, 2021

Imidazole propionate



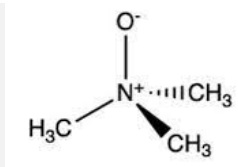
Its level is significantly increased during T2D and is associated with insulin resistance. Zhang et al, 2020; Zhao et al, 2021

Trimethylamine (TMA)



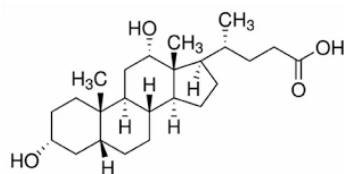
In hepatocytes it is metabolised by flavin monooxygenases 3 to yield TMA-N-oxide (TMAO). Xie et al, 2021; Vendrik et al, 2020

TMA-N-oxide (TMAO)



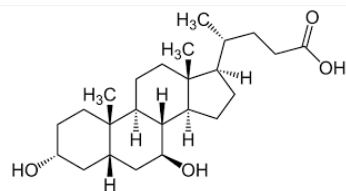
Increased systemic TMAO level observed during diabetes and obesity. Xie et al, 2021; Vendrik et al, 2020

Deoxycholic acid



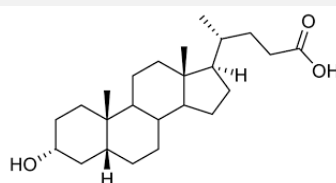
Agonist for farnesoid X receptor (FXR) and Takeda G-protein coupled receptor (TGR5). Tian et al, 2020; Rossen et al, 2015
Increases hepatic insulin sensitivity, insulin secretion from the pancreas.

Ursodeoxycholic acid



Agonist of FXR and TGR5. Tian et al, 2020;
Increases hepatic insulin Rossen et al, 2015
sensitivity, insulin secretion
from the pancreas.

Lithocholic acid



Agonist of FXR and TGR5. Paramsothy et al,
Increases hepatic insulin 2019; Mitrea et al,
sensitivity, insulin secretion 2022
from the pancreas.

CONCLUSION

Research findings support GBA existence which can be modulated by the host signalling pathways, including the metabolites secreted by the gut microbiome. Gut dysbiosis can be overcome by the transfer of normal gut microbial population using FMT from healthy individuals to those who are dysbiotic. An altered gut microbiota can lead to various diseases of the GIT, including neuropsychiatric and neurological disorders. IBS, IBD and constipation are such GIT conditions that can be modulated by FMT from the healthy donors to the recipients. FMT increased the diversity and alters the composition of microbial population in the recipient fecal and colon samples. Differences across bacterial phyla are observed between the normal and those suffering from dysbiosis. Microbial metabolites are the major modulator of biological processes various tissues/organs, including the gut in the host. These metabolites have major effect in the host when their production is compromised due to dysbiosis and are key in IBS, IBD and constipation progression. Altered control of the microbiota-GBA due to gut dysbiosis could be the reasons for the onset and progression of some neurological disorders. Preliminary data obtained indicate that neurological disorders such as AD, PD, ASD and depression can be effectively treated by FMT, though some

findings say the opposite. Neuroinflammation is a typical feature of most neurological disorders, and which gets elevated due to gut microflora compositional alteration. Dysbiotic gut microbiota impairs normal immune system and metabolic pathways which stimulate hippocampal proinflammatory signalling via the GBA thereby inducing depression and anxiety-like features in mice. Metabolic profiling study shows that metabolites level modulation by the gut microbiome can profoundly influence GBA and could serve as biomarkers in potential treatment strategy for ASD. In conclusion, several pre-clinical and clinical findings show FMT as potential therapeutic intervention for transmission and treatment of intestinal and neurological disorders. Future studies on large randomized-controlled trials in a population are required to understand FMT in human diseases related to gut dysbiosis.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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Identification of Anti-Cancer Lead Compounds from *Crocus sativus*: A Comprehensive Molecular Docking and QSAR Investigation

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ABSTRACT

Conventional cancer treatments like chemotherapy and radiotherapy are frequently bottlenecked by high toxicity, severe side effects, and astronomical development costs. Consequently, plant-derived bioactive secondary metabolites have emerged as promising, low-toxicity alternatives in modern drug discovery. Saffron (*Crocus sativus* L.) contains four major therapeutic carotenoids and monoterpene aldehydes: crocin, crocetin, picrocrocin, and safranal. This study evaluates their therapeutic efficacy against the tumor suppressor protein p53 using an integrated in silico approach pairing molecular docking with Quantitative Structure-Activity Relationship (QSAR) modelling. Molecular docking studies revealed that all four compounds localized within the vital DNA-binding domain of p53. Picrocrocin demonstrated the highest binding affinity (-6.01 kcal/mol), followed by safranal (-5.01 kcal/mol), crocetin (-4.43 kcal/mol), and crocin (-4.32 kcal/mol). Refined QSAR equations identified Topological Polar Surface Area (TPSA), octanol-water partition coefficient (LogP), and Molecular Refractivity (MR) as pivotal structural descriptors influencing biological activity. These computational findings provide a structural roadmap for prioritizing saffron-derived lead candidates, with safranal and picrocrocin standing out as optimal scaffolds for further preclinical optimization.

KEYWORDS: p53, saffron, bioactive metabolites, anti-cancerous, molecular docking, QSAR.

INTRODUCTION

The scientific exploration of bioactive metabolites present in plants is emerging as a competent resource in the competition for developing new drugs (Somasagara et al., 2012). Cancer is amongst the major health threats claiming millions of lives around the world on a regular basis (Jemal et al., 2009). In the present decade, the prevalence of cancer, its recurrence and severe side-effects of chemotherapeutic treatments brought about the resurgence of interests making the use of herbal preparations as more efficacious drugs with meager or no side-effects. Spices are dietetic food components ingested by most of the world population regularly to heighten the taste and

flavour. (Premankur and Ramesh, 2010). The extracts of typically used condiments was shown to have high cytotoxicity on tumoral cell cultures (Unnikrishnan and Kuttan, 1988). Saffron, included amongst the most expensive spices, has been historically employed as a food colorant, cosmetic and drug in medicine (Amin and Buratovich, 2002; Samarghandhan and Borji, 2014). The cultivation of saffron can be dated back to 2500-1500 BC and originated possibly in Iran, Greece and later became widespread in China, India, Eastern Europe and Mediterranean region (Tammara, 1987). It is now cultivated diversely all over the world for its flavouring and medicinal perspectives.

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Saffron spice is produced from the parched *Crocus sativus* L. stigmas, belonging to the Iridaceae family (Srivastava et al., 2010). In addition to riboflavin saffron possesses a rich source of carotenoids (Gutheil et al., 2012). *C. sativus*, a stem-less perennial herb (Rios et al., 1996), prefers infriable, loose, well-watered and well-drained calcareous soil. The plant is characterized by its narrow leaves and a corm which is a fleshy bulb (Kumar et al., 2009). According to chemical analyses four principle active ingredients isolated from saffron which composed of crocin, crocetin, picrocrocin and safranal Figure1. Crocin is a crocetingentiobiase ester and is water soluble. The major component of crocin, crocetin, is a diterpenic carotenoid (the aglycon of crocin) is 88'diapo-88'-carotenoic acid (Giaccio, 2009). Picrocrocin is a monoterpene glycoside (4-(β -D-glucopyranosyloxy)-2,6,6-trimethyl-1-cyclohexene-1-carboxyaldehyde). Picrocrocin is the chemical contributing to the bitter taste of saffron. Safranal, (2,6,6-trimethyl cyclohexa-1,3-dien-1-carboxyaldehyde) which is synthesized by the deglucosylation of picrocrocin (Schmidt et al., 2007; Zhang et al., 1994; Nair et al., 1995) constitutes the volatile agent of saffron whereas crocin and crocetin can be categorized as dyes responsible for colouring (Premankur and Ramesh, 2010). In addition to other carotenoids crocin, crocetin, picrocrocin and safranal are among of the most important saffron components to have anticancer and antitumor properties (Hosseini et al., 2018a; Yao et al., 2018). The method of operation of anti-cancerous and tumoricidal attributes of the engaging metabolites of saffron, crocin, crocetin, picrocrocin, and safranal are still unclear (Abdullaev and Frenkel, 1999). Crocetin, the major constituent of saffron, has sparked research curiosity owing to its multiple pharmaceutical impacts, including chemotherapeutic properties (Li et al., 2017). Additionally, reports claimed that carotenoids in saffron induce apoptosis, inhibit proliferation and synthesis of DNA, RNA, the suppressive effect on free radical reactions, and proteins in various classes of cancer cells

(Bathaie et al., 2013). It is an established fact that the cellular ratio of Bcl-2/Bax makes a cell either prone to cell proliferation or apoptosis, i.e., a higher Bcl-2/Bax ratio prevents a cell from undergoing apoptosis since Bcl-2 is part of the anti-apoptotic family whereas Bax is pro-apoptotic. Therefore, a lower Bcl-2/Bax ratio will induce cell death (Sarbia et al., 1997; Sedlak et al., 1995). Therefore, from literature survey, research indicates that crocetin, which is a key bioactive metabolite of saffron, increases cell permeability and induces cell death (Escribano et al., 1996). The remaining carotenoids have been reported to restrain DNA and protein synthesis (Abdullaev and Espinosa-Aguirre, 2004). P53, commonly regarded as the "guardian of the genome" is a nuclear transcription factor. It is observed to have been mutated in every kind of cancer. p53 is also pro-apoptotic i.e in cells which have DNA damage or are undergoing stress, p53 is found to induce apoptosis (Sionoy and Haupt, 1999; Prives and Hall, 1999; Vousden and Lu, 2002; Lacroix et al., 2006; El-Deiry, 2003). In this study the therapeutic efficiency of the bioactive metabolites of saffron, crocin, crocetin, picrocrocin and safranal have been studied to discover whether these metabolites can induce p53-mediated apoptosis in cancer cells. Molecular docking is used to model interactions of the receptor which is generally a protein and a ligand which might be another protein or any small molecule such as a drug etc. and predicts the different ligand conformations on the catalytic site of the protein. The finest docked configuration can be chosen based on some docking scores generated by the tool being used such as ligand's binding energy, its efficiency and other parameters based on the acquired attributes of the tool being used (Meng et al., 2011). The docking tool uses different algorithms and most popularly used is Genetic Algorithm. Since, the bioactive components are probable anti-tumour agents therefore Quantitative Structure-Activity Relationship, QSAR, evaluation was executed to determine their chemical attributes along with varying biochemical functions such as LD₅₀ and IC₅₀

values. To develop an association between the chemical properties of substances to their biological activities and to attain a reliable paradigm for prognostication of new chemical entities' activities on which QSAR can be performed (Patel et al., 2014).

METHODOLOGY

Retrieval of frameworks of the bioactive metabolites

The carotenoids' three-dimensional frameworks namely crocin and crocetin, and the monoterpene aldehydes namely picrocrocin and safranal were retrieved from ChemSpider (Pence and William, 2010) with ChemSpider ID 4444645 for crocin, 4444644 for crocetin, 115678 for picrocrocin and 55000 for safranal. The structures from ChemSpider were in MOL format and were therefore transformed to PDB format using the offline variant of the software Open Babel; OpenBabel-2.4.0 (O'Boyle et al., 2011). The 3D organization visualization of the carotenoids was done with the aid of UCSF Chimera; Chimera 1.11.2 (Pettersen et al., 2004).

Physiochemical properties

The physicochemical attributes of the four metabolites of saffron had been retrieved from PubChem (Kim et al., 2016) in the form of melting point, molecular weight, molecular formula, number of hydrogen bond's donor and acceptor, number of rotatable bonds, TPSA, monoisotopic mass, XLogP3-AA, in addition to number of heavy atoms, numbers of stereocenter for defined atoms and defined bonds and covalently bonded atom count. The attributes mentioned were used for comparison among the compounds in terms of drug-likeness and structural diversity.

Molecular Binding Prediction: Molecular Docking

The structure of p53 protein was retrieved from Protein Data Bank (Protein ID- 1TUP) and preparation was accomplished by the standard steps required for docking. Ligand- receptor molecular binding inquiry was executed using offline AutoDockTools-1.5.6 (Morris et al., 1996) on windows platform. The employment of Auto Dock Tools was achieved with the

available MGL tools. Docking of the four bioactive compounds crocin, crocetin, picrocrocin and safranal against p53 was completed with the aid of Lamarckian Genetic Algorithm. The p53 was kept as the macromolecule which has been kept as rigid and the ligands i.e. crocin, crocetin, picrocrocin and safranal were kept flexible. The grid was maintained in a specific manner so that the macromolecule and the ligands were submerged within the given grid parameters for the four individual ligands against the macromolecule.

Quantitative Structure Activity Relationship Investigation

Quantitative structure Activity Relationship, QSAR was completed with a non-networked software tool Easy QSAR (Asthana et al., 2014). Crocin, crocetin, picrocrocin and safranal were analysed in relation to their molecular properties. The activity used for crocin, picrocrocin and safranal was Lethal Dose 50, LD₅₀ (Abdullaev and Espinosa-Aguirre, 2004) whereas the activity used for crocin and crocetin was Inhibitory Concentration IC₅₀ (Kim et al., 2016). The molecular features used as descriptors were created for the individual metabolites using Custom Computation in ChemDes (Jie et al., 2015). The molecular properties used as descriptors were Topological Polar Surface Area (TPSA), squared Moriguchi octanol-water partition coefficient (logP₂), hydrophilic factor (Hy), Unsaturation index (Ui), Moriguchi octanol-water partition coefficient (logP), and molecular refractivity (MR). The input files provided for the generation of descriptor files were first and foremost transformed from mol format into smiles format.

RESULTS

Physiochemical properties

The physiochemical properties of the four bioactive metabolites are mentioned in the table, some of which were also salvaged from ChemSpider, apart from PubChem database (Table 1). The metabolites were found to exhibit discrepancy in polarity, molecular

size and flexibility with crocin representing the largest polar compound and safranal reportedly small and least polar.

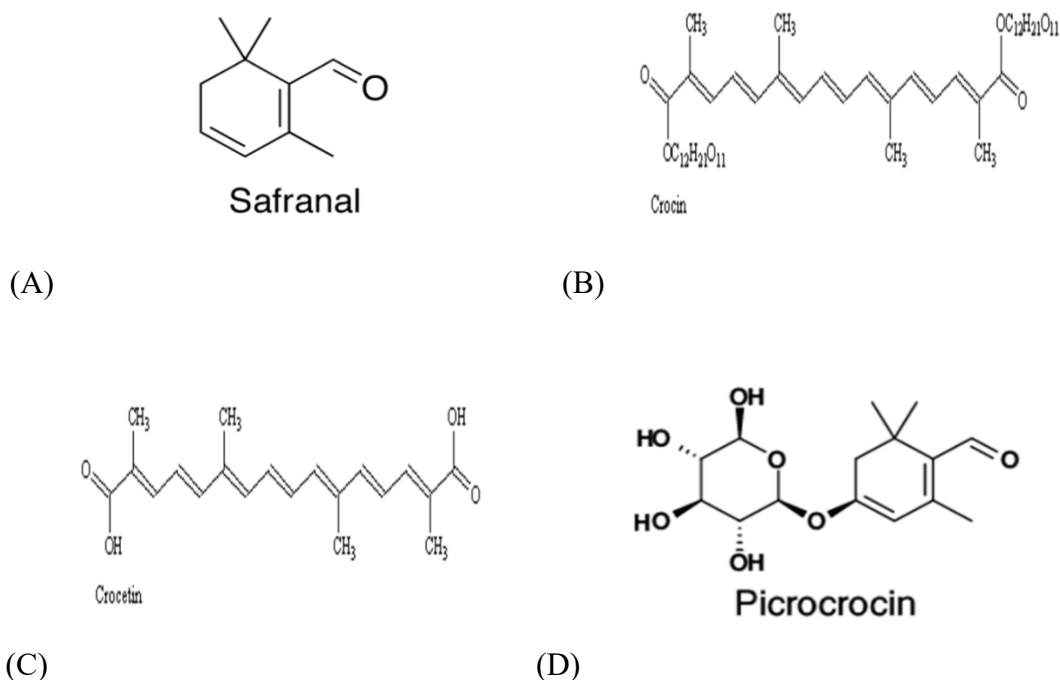


Figure1: Showing the four bioactive compounds found in saffron namely: crocin, crocetin picrocrocin and safranal.

Molecular Docking Analyses

In this current study molecular docking of p53 with the four individual metabolites crocin, crocetin, picrocrocin, and safranal was performed employing AutoDock Tools and 10 docking conformations were developed for all the four metabolites. However, the conformer with the greatest bonding energy has been reported. The factors reported in Table 2 are ligand proficiency, bonding energy, inhibition constant, inter-molecular energy, vdw-hb-desolving energy, unbound energy, total intrinsic energy, rotational energy, cIRMS, ref RMS. The maximum binding energy was noticed in picrocrocin with -6.01 followed by safranal with -5.01, crocetin with -4.43 and crocin with -4.32 respectively. The docking conformations which are represented in Figure 3, shows crocin, crocetin, picrocrocin, and safranal interacting with the DNA-binding

junction of the p53 molecule. This observation could be accounted for, because the active metabolites of saffron inhibit cancer growth and proliferation by inhibiting DNA and RNA synthesis. Therefore, from the binding energies of all the four bioactive metabolites, picrocrocin shows maximum binding affinity with the most favourable predicted binding affinity and was trailed by safranal, crocetin and crocin. The graph of binding energy versus conformations had been generated for the total four bioactive metabolites and is represented via Figure 2. Mostly the interactions between p53 and the carotenoids revealed Vander Waals interactivity and few alkyl residues in addition to hydrogen bonded interactions. The amino acid interaction of p53 and the carotenoids are presented in Table 3, with picrocrocin showing

interactions with Gln A:167, Ala B:276, Cys B:277, Ser B:121, Thr B: 123, and Gln B136.

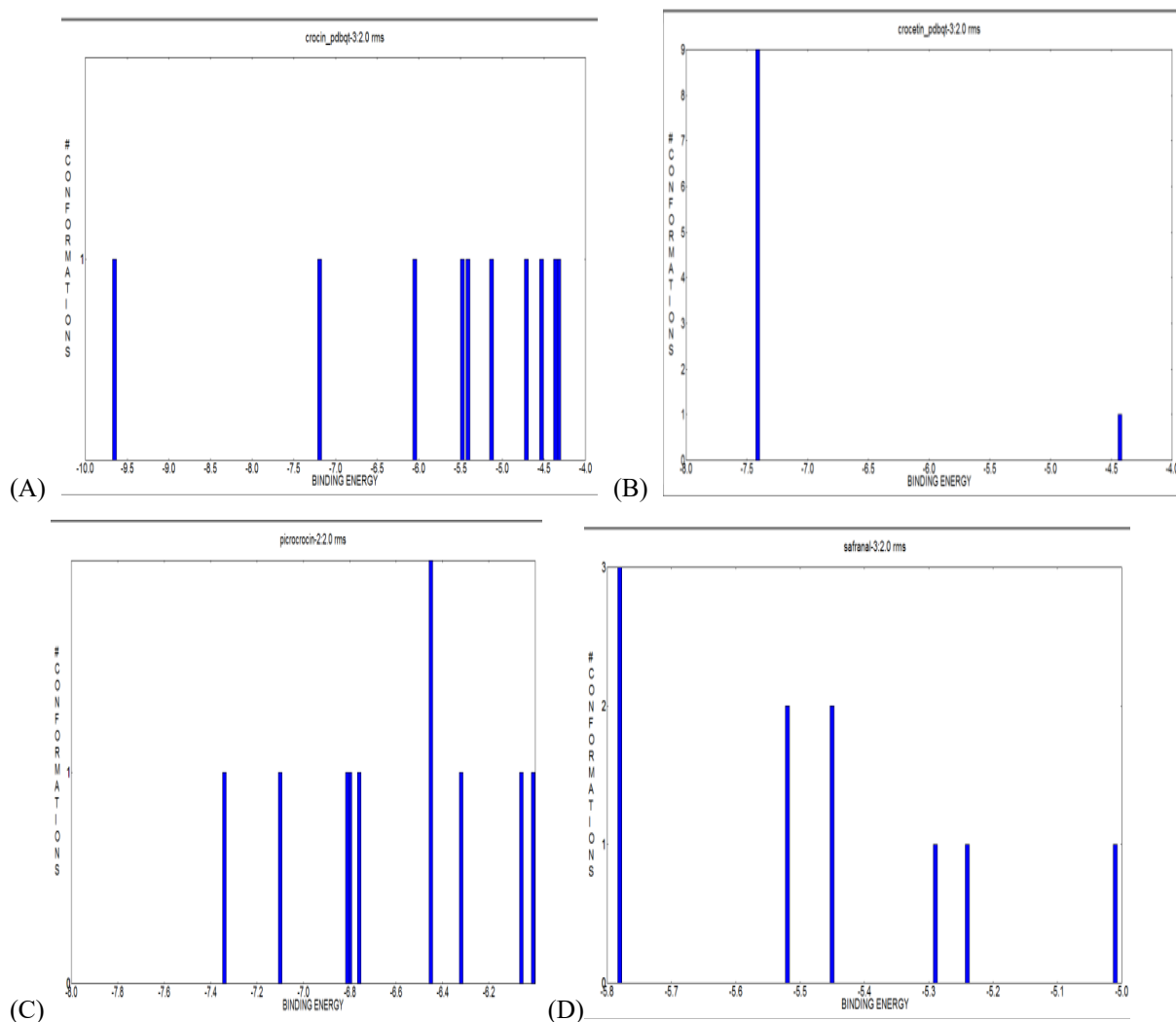


Figure 2: The graph of binding energy vs. conformations (2.0 clustering) of (A) crocin, (B) crocetin, (C) picrocrocin, (D) safranal. This was generated by the integrated commands in AutoDock tools after the conformations were formed. Out of 10 conformations, the best pose was selected based on their binding energies.

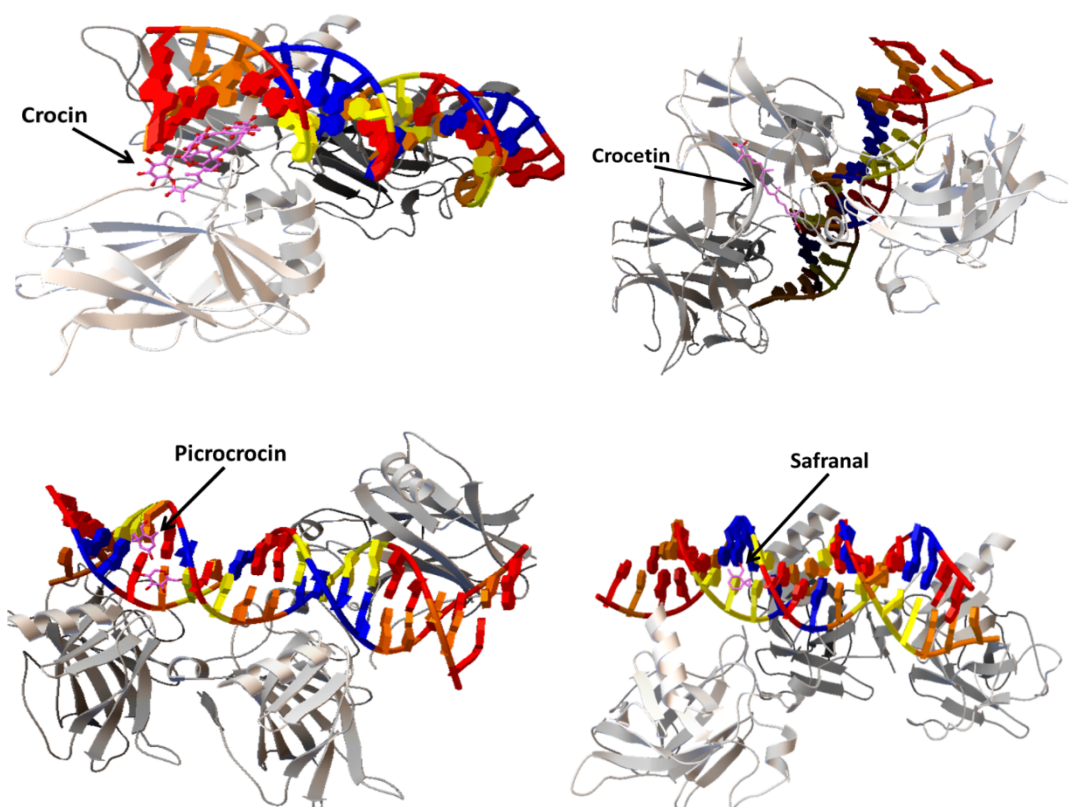


Figure3: Docking results of the four bioactive metabolites of saffron, crocin, crocetin, picrocrocin, safranal with p53 as generated using AutoDockTools-1.5.6.Lamarkian Genetic algorithm was chosen while carrying out the molecular docking sessions between the rigid macromolecule (p53) and the flexible ligands (i.e crocin, crocetin, picrocrocin and safranal respectively).

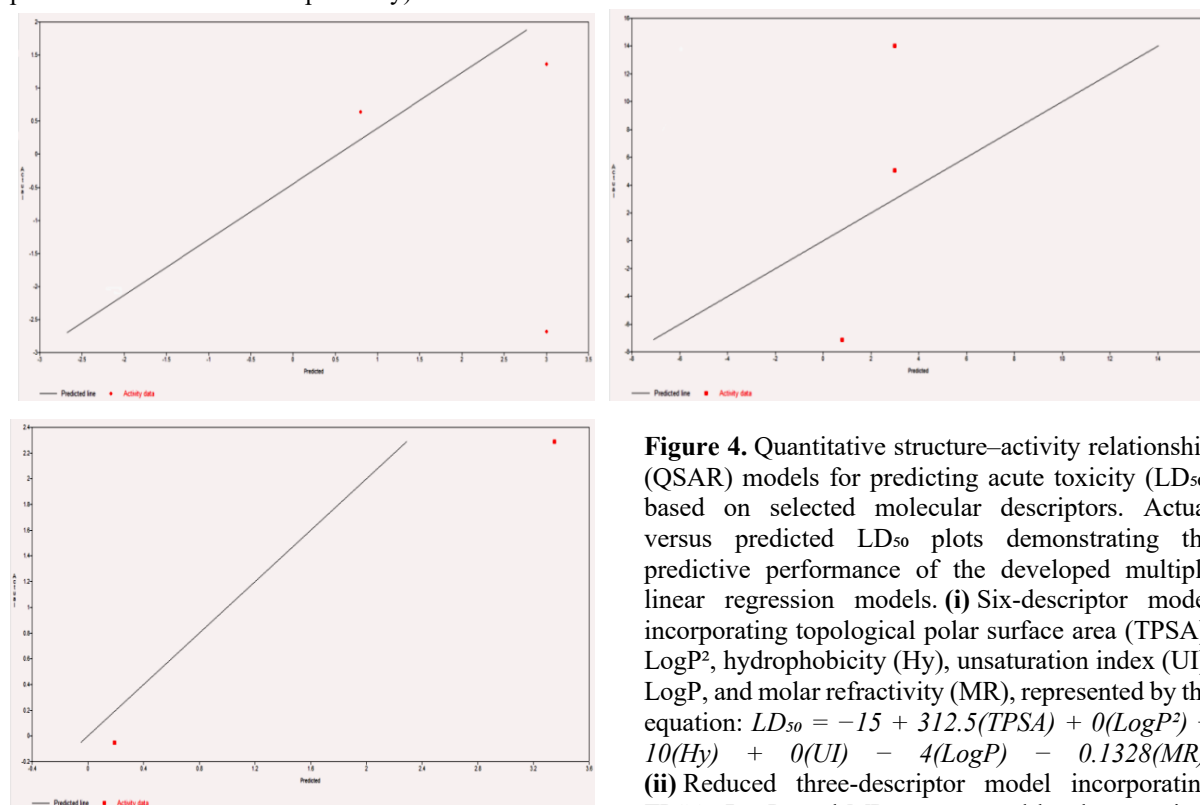


Figure 4. Quantitative structure–activity relationship (QSAR) models for predicting acute toxicity (LD_{50}) based on selected molecular descriptors. Actual versus predicted LD_{50} plots demonstrating the predictive performance of the developed multiple linear regression models. (i) Six-descriptor model incorporating topological polar surface area (TPSA), LogP^2 , hydrophobicity (Hy), unsaturation index (UI), LogP , and molar refractivity (MR), represented by the equation: $LD_{50} = -15 + 312.5(TPSA) + 0(LogP^2) - 10(Hy) + 0(UI) - 4(LogP) - 0.1328(MR)$. (ii) Reduced three-descriptor model incorporating TPSA, LogP , and MR, represented by the equation: $LD_{50} = 5.5313 - 0.0195(TPSA) - 1.2500(LogP) - 0.0313(MR)$.

Table 1: The chemical and physical properties of crocin, crocetin, picrocrocin have been summarized in the table.

Sl. No.	Parameters	Bioactive compounds			
		Crocine	Crocetin	Picrocrocin	Safranal
1	PubChem CID	5281233	5281232	130796	61041
2	Molecular Formula	C ₄₄ H ₆₄ O ₂₄	C ₂₀ H ₂₄ O ₄	C ₁₆ H ₂₆ O ₇	C ₁₀ H ₁₄ O
3	Molecular Weight (g/mol)	976.972	328.408	330.377	150.221
4	Melting Point	185°C	285°C *	209.65°C *	< 25°C
5	Hydrogen Bond Donor Count	14	2	4	0
6	Hydrogen Bond Acceptor Count	24	4	7	1
7	Rotatable Bond Count	20	8	4	1
8	TPSA	391 A ²	74.6 A ²	116 A ²	17.1 A ²
9	Monoisotopic mass (g/mol)	976.3799	328.167	330.168	150.104
10	XLogP3-AA	-2.5	5.4	-0.5	2.1
11	Heavy atom count	68	24	23	11
12	Defined Atom Stereocenter Count	20	0	6	0
13	Defined Bond Stereocenter Count	7	7	0	0
14	Covalently Bonded Unit Count	1	1	1	1

* The melting points of crocetin and picrocin have been retrieved from ChemSpider.

Table 2: The different parameters generated because of docking p53 with the different ligands (crocine, crocetin, picrocrocin, safranal) have been computed and listed above. The values were computed with Auto Dock tools while generating the conformations along with their binding energies and other computation values.

Receptor Ligand	1TUP			
	Crocine	Crocetin	Picrocrocin	Safranal
Binding energy	-4.32	-4.43	-6.01	-5.01
Ligand efficiency	-0.06	-0.18	-0.26	-0.46
Inhibition constant (μmol)	686.82	570.48	39.45	211.05
Intermolecular energy	-9.68	-7.41	-7.2	-5.01
vdw-hb-desolving energy	-0.96	-6.75	-7.12	-4.96
Electrostatic Energy	-0.06	-0.66	-0.08	-0.05
Total internal energy	-7.95	-0.71	-0.28	0
Torsional energy	5.37	2.98	1.19	0
Unbound energy	-7.95	-0.71	-0.28	0
clRMS	0	0	0	0
refRMS	24.33	34.03	35.66	31.77

Table 3: Showing the amino acids interacting with the p53 (1TUP) molecule, along with their position, chain and the type of interactions.

Receptor	Ligand	Amino acid position	Type of interaction
1TUP	Crocin	Lys C: 120, Glu C: 198, Thr B: 211, Ser B: 96, Glu B: 171	Unfavourable donor-donor interactions
		Asn B: 210, Gly C: 199	Conventional hydrogen bond
		His B, 168, Lys C: 139	Alkyl
		Cys C: 277, Asn C: 235, Ser C: 121, Thr C: 123, Arg B: 249, Gln B: 167, Thr C: 140, Val B: 97, Leu C: 201, Thr B: 170, Phe B: 212, Arg B: 213, Val B: 172, Arg C: 196	Van der Waals
	Crocetin	Arg B: 248	Hydrogen bond
	Picrocrocetin	Gln A: 167, Ala B: 276, Cys B: 277, Ser B: 121, Thr B: 123, Gln B: 136	Van der Waals
		Ser A: 166	Unfavourable donor-donor bond
		Lys B: 139	Alkyl
	Safranal	Ser A: 166, Gln A: 165, Gln A: 167, Gln B: 136, Ser B: 121, Lys B: 120	Van der Waals
		Ala B: 276, Cys B: 277	Alkyl

Quantitative Structure Activity Relationship Analyses

Since crocin, crocetin, picrocrocetin, safranal can be potential drug candidates therefore Quantitative Structure-Activity Relationship, QSAR was carried out to anticipate their biological action with the chemical structures. Crocin, picrocrocetin and safranal were analysed in relation to their molecular properties i.e the descriptor file contained molecular properties as generated from ChemDes and the activity chosen was LD₅₀. After performing QSAR studies a statistical analysis was initiated from which the F statistics calculated was 0.733 with a critical F of 19.33. The percentage contribution of each descriptor to activity was 49.75% of TPSA, 9.48% of LogP₂, 25.19% of Hy, 8.33% of UI, 63% of LogP, and 41.68% of MR. Also, the correlation of descriptors with activity generated was 0.71 for TPSA, 0.31 for LogP₂, -0.50 for Hy, 0.29 for UI, -0.79 for LogP, and 0.65 for MR. A plot was generated of actual vs. predicted activity with the QSAR equation Figure 4 (i). The actual values were 3mM, 3mM, and 0.8mM for crocin, picrocrocetin

and safranal respectively and the predicted values were 14.02, 5.06 and -7.12. Since for a better prediction the percentage contribution of descriptor to activity is around 50% and for a good correlation the threshold chosen was around 0.7 therefore the analysis was re-executed by taking only TPSA, LogP and MR as descriptors. A plot was generated for the real versus expected activity with the generated QSAR equation Figure 4 (ii). The F statistics calculated was 0.28 and the critical F value was 19.16. The predicted values were -2.69, 1.36 and 0.64. Using IC₅₀ values of crocin and crocetin QSAR studies was again carried out to summarize their activity with their chemical structure. The F statistics calculated was 0.32 and the critical F value was 233.39. The percentage contribution of each descriptor to activity and correlation of descriptors with activity was not reported. This could have been an outcome resulting from fewer number of parameters chosen for the study. The actual IC₅₀ values were 3.35 mmol/l and 0.19 mmol/l, and the predicted values calculated were 2.29 and -0.05 for crocin and crocetin respectively. A plot

was generated for actual vs. predicted activity along with the QSAR equation Figure 5 (iii).

DISCUSSIONS

The survey on the naturopathic treatment using saffron to obviate and in curing of cancer was rooted on the extract from the parched *Crocus sativus* stigmas having anti-cancerous properties (Srivastava et al., 2010; Zhang et al., 1994). This study explored the anticancer potential of saffron metabolites through docking and QSAR analysis. The four active carotenoid secondary metabolites of saffron viz. crocin, crocetin, safranal and picrocrocin reportedly possess diverse pharmacological impacts including cytoprotective, antioxidant as well as antitumor effects via inhibition of cell growth, apoptosis, etc. (Abdullaev and Frenkel, 1999; Amin and Buratovich, 2007). p53 typically regarded as the “guardian of the genome” is a gene regulating cellular stress and genetic damage and is found to have oncogenic potential when mutated. p53 is found to induce its pro-apoptotic functions in response to cellular insults such as DNA damage (Sionoy and Haupt, 1999; Vousden and Lu, 2009). It is well documented that all the four bioactive metabolites of saffron can suppress the proliferation of cancer cells both *in-vitro* and *in-vivo*. Crocetin has been evidenced to hamper the multiplication of tumor cells by enhancing the proportion of Bax/Bcl-2, which in turn induces apoptosis and ultimately tumour formation (Sarbia et al., 1997; Sedlak et al., 1995). From the studies, the discrepancy of the predicted LD₅₀ from actual LD₅₀ value was the least in safranal followed by the actual and predicted IC₅₀ value of crocetin, crocin and LD₅₀ value of picrocrocin and crocin. Therefore, safranal can be further tested for potential anti-cancer and anti-tumor drug candidate.

Despite saffron and its components possessing many therapeutic effects they do also possess their fair share of limitations. Safranal, though show several pharmacological effects such as inflammation and antioxidant activity, it is an aromatic substance and therefore represent a major volatile component of saffron

(Esmaealzadehet al., 2023). Crocin had been studied extensively and was found to exhibit pharmacological effects as a cardioprotectant and neuroprotectant and is also water soluble, but has poor oral absorptivity (Song et al., 2021). In the intestine crocin is broken down into crocetin and this substance can reach CNS by penetrating blood-brain barrier transcellular diffusion hence is effective in neurodegeneration, but its plasma concentration level is low (Hosseini et al., 2018b). Additionally, since very limited numbers of compounds were used for QSAR analysis there is a constrained factor in the model stability. With few data points the model statistics can be unstable, and a single deviant can distort the apparent relationship between structure and activity.

Regardless, the study presents a relevant and worthwhile preliminary computational investigation into the anticancer potential of saffron-derived metabolites and further analysis can be carried out such as checking which metabolite is acting against which form of cancer and how much is their potential to curb the disease. Additionally, the compounds can be considered promising leads as therapeutic candidates and could be explored more in this direction. Picrocrocin is relatively less studied and its binding affinity with p53 being the highest in this study has open a way for more exploration on this compound.

CONCLUSIONS

The present study accentuates the promising anti-cancer quality of saffron's bioactive compounds specifically crocetin, crocin, picrocrocin and safranal, by means of physicochemical properties, molecular docking simulations and QSAR analyses. Pubchem and Chempidder obtained data inveterate effective drug-like properties supported by molecular docking analyses with binding energies of -6.01 kcal/mol (picrocrocin), -5.01 kcal/mol (safranal), -4.43 kcal/mol (crocetin), and -4.32 kcal/mol (crocin), predominantly driven through van der Waals, alkyl, and interactions between hydrogen bridge with key residues (Table 3). These binding energies suggest

effective inhibition and blockage of DNA and RNA synthesis mechanisms successfully curbing cancer cells proliferation and induce apoptosis. Refined key descriptors such as TPSA, LogP, and MR in QSAR analyses yielded F-statistics up to 0.733 and correlations ≥ 0.65 further validating structure activity correlations between the actual and predicted values, underscoring their structural stability as drug candidates. To summarize, saffron's metabolites have promising potential as tumor suppressants with safranal as the most viable candidate warranting further preclinical validation because of its superior predictive binding accuracy. Further research could be done by evaluating combinations with other chemotherapeutics or natural products to increase these metabolites' effectiveness.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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Sub-barrier Fusion Cross Section and Its Dependency on Neutron Transfer Form Factor for $^{18}\text{O} + ^{116}\text{Sn}$ system

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ABSTRACT

The $^{18}\text{O} + ^{116}\text{Sn}$ system's fusion excitation functions were revisited in the energy regime below the Coulomb barrier, where the experimental fusion cross sections enhancement was noted compared to that of the simple barrier penetration model. To understand such enhancement, analyses were carried out with different values of transfer coupling strength or transfer form factor in the coupled channels formalism. The ground state Q value is positive for this system. A comparative study of the system selected for this work with different coupling schemes indicated that the coupling of 2 neutron transfer channel with the collective excitations is the reason behind such sub-barrier fusion enhancement. To carry out such calculations considering neutron transfer coupling, a parameter called transfer form factor is required which depends on a factor called transfer coupling strength. It is discovered that as the transfer coupling strength is increased or decreased, the fusion cross-section likewise increases or decreases below the barrier energy and exhibits the opposite trends above it. Such variations have been emphasized in this work through the system considered.

KEYWORDS: Sub-barrier fusion cross section, Neutron transfer, Transfer form factor, Q – values, CCFULL.

INTRODUCTION

The heavy-ion nuclear fusion dynamics at energies surrounding the Coulomb barrier is strongly influenced by coupling to different reaction channels (Deb et al., 2022). Many experimental results clearly conveyed the fact that coupling to collective excitations could enhance the sub-barrier fusion cross sections, i.e., the fusion cross sections at energies below the barrier on comparison with the one-dimensional barrier penetration model (1DBPM) predictions (Deb et al., 2022; Stefanini et al., 1995a, 1995b). Few experiments even pointed out that the sub-barrier fusion enhancement that was seen is due to the neutron transfer that takes place in addition to the inelastic couplings (Dasso et al., 1983a, 1983b). However, an unambiguous statement cannot be made regarding the role of transfer reactions in fusion in the presence of strong inelastic couplings. The role of various couplings in the behaviour of sub-barrier fusion is still being investigated because the present experimental and theoretical research are

insufficient to draw firm conclusions. More experiments on different projectile-target combinations will produce enough data to study theories and formulations to be made regarding the role of neutron transfer on the sub-barrier fusion cross section. Most of the experiments were carried out on systems having positive ground state Q value neutron transfer channels because they create barrier energy of lower values than the inelastic couplings and, therefore, can be identified. In this paper, the role of different couplings, including inelastic and neutron transfer, in sub-barrier fusion is studied for the $^{18}\text{O} + ^{116}\text{Sn}$ system. To highlight the pertinent significance of couplings to collective states and neutron transfer channels having $+Q$ values at ground state as well as the variations of the parameters involved in the cross-section formula, we examine the fusion cross-section measurements from Ref. (Deb et al., 2020) for this same system. This $^{18}\text{O} + ^{116}\text{Sn}$ system possesses positive Q value for 2 neutron transfer channels. The Sn isotopes are

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collective in nature as they have the lowest quadrupole and octupole states. A complete level structure of Sn has been studied up to excitation energy of 4.3 MeV and the existence of two- and three-quadrupole phonon states could be identified (Raman et al., 1991). The $B(E_2) \uparrow$ values of the transitions from the first 4^+ state and the second and third 2^+ states are found to be more compared with that of the single particle estimates, therefore indicating that these states have a character of two-phonon vibrational state. The $J^\pi = 1^-$ states have been studied in many even-even isotopes of Sn nuclei (Bryssinck et al., 1999), and this has been identified as a member of the multiplet of the mixed quadrupole - octupole ($2^+ \otimes 3^-$) multiphonon states. Therefore, there is enough experimental data to confirm that the Sn isotopes have two or more phonon states. The $^{18}\text{O} + ^{116}\text{Sn}$ system studied enables us to study the fusion excitation function due to coupling to positive Q value neutron transfer channels. The ground state Q values for the different neutron transfer channels are given in Ref. (Deb et al., 2020).

Role of neutron transfer in sub-barrier fusion

The optimum Q value (Q_{opt}) controls nucleon transfer between interacting partners in heavy ion driven nuclear processes (Deb et al., 2020) Q_{opt} , derived from smoothly matching the trajectories before and after the transfer (Liang et al., 1994) is given by

$$Q_{\text{opt}} = \left(\frac{Z_p' Z_t'}{Z_p Z_t} - 1 \right) E_{\text{c.m.}} \quad (1)$$

where Z_p and Z_t are the atomic numbers of projectile and the target respectively, Z_p' and Z_t' are the atomic numbers of the ejectile and the recoil nucleus respectively, and $E_{\text{c.m.}}$ is the energy of the projectile in the center of mass frame. The relevant quantity to be considered for the transfer channel is the difference between the ground state Q value and the optimum Q value. For neutron transfer channels $Q_{\text{opt}} = 0$ because the atomic number of the interacting partners remain the same before and after the reactions as neutrons being neutral in charge. As a result, the ground state Q value is

considered in the current work for interpreting fusion cross-sections. Even though the Q value is positive for numerous neutron transfer pathways, only valence neutrons (primarily one or two neutron transport channels with ground state Q values that are positive) contribute significantly to fusion. Additionally, if coupling to collective states is less prominent for spherical or magical nuclei, the substantial contribution from the transfer channels can be anticipated (Khushboo et al., 2017). The transfer form factor (F), which is generated from the empirically obtained transfer probability and is provided by the following equation (Hagino et al., 1999; Dasso & Vitturi, 1986), is a transfer-related parameter needed to include transfer coupling in the computation

$$F = F_t \frac{dV_N}{dr} \quad (2)$$

where V_N is the ion-ion nuclear potential and the factor, F_t , is known as the transfer coupling strength which is expressed as

$$F_t = \frac{\beta_p R}{3A_T} \quad (3)$$

where β_p is the pairing deformation parameter scale which plays the analogous role as the standard dynamical deformation parameter, β . Just as β displays the character of inelastic transitions, β_p measures the collective strength of the pair modes. Here R and A_T are the radius and mass of the target respectively. Thus, the transfer form factor is radial dependent which can be further simplified as (Mahon et al., 1997)

$$F = F_t \frac{1}{\sqrt{4\pi}} \exp \left[-\frac{(r-R_B)}{1.2 fm} \right] \quad (4)$$

where R_B is the barrier radius. The transfer probability, in the form of transfer form factor (Saha et al., 1994), is written as $P(r_o, Q_x) =$

$$\frac{\pi}{\sigma^2} |F(r_o, Q_x)|^2 \exp \left[-\frac{(Q_x - Q_{\text{opt}})^2}{2\sigma^2} \right] \quad (5)$$

where $\sigma = \sqrt{\frac{\hbar^2 \alpha r_o}{2}}$. This Eq. (5) gives the probability of transfer to a given excited state x with Q value Q_x . α is the amplitude for the colliding system to be in a channel x after the reaction ($t = \infty$) and is given by

$$\alpha_x(\infty) = \frac{1}{i\hbar} \int_{-\infty}^{\infty} F_x(r, Q_x) e^{i \frac{(Q_x - Q_{opt})t}{\hbar}} dt, \quad (6)$$

where F_x is a form factor describing the transition from the incoming channel to the channel x having Q value Q_x . The integral in Eq. (6) is evaluated by considering the trajectory around the distance of closest approach, r_o , given by

$$r(t) = r_o + \frac{1}{2} \ddot{r}_o t^2 \quad (7)$$

where $\ddot{r}_o$ is the acceleration at r_o which is calculated for the entrance and exit channels by assuming a Coulomb trajectory using the relation

$$r_o = \frac{Z_1 Z_2 e^2}{2(E_{c.m.} + Q)} \left(1 + \operatorname{cosec} \frac{\theta_{c.m.}}{2} \right) = d_0 \left(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}} \right) \quad (8)$$

The d_0 value can be found out by knowing the $\theta_{c.m.}$ value that can be determined from the transfer measurement. Thus, using Eq. (4) and Eq. (7), the integral in Eq. (6) is evaluated

$$\begin{aligned} & \text{as } \alpha_x(\infty) = \\ & \frac{1}{i\hbar} F_x(r_o, Q_x) \sqrt{\frac{2\pi}{\alpha \ddot{r}_o}} \exp \left[-\frac{(Q_x - Q_{opt})^2}{2\hbar^2 \alpha \ddot{r}_o} \right] \end{aligned} \quad (9)$$

Thus, the transfer probability is obtained as in Eq. (5) using $P(r_o, Q_x) = |\alpha_x(\infty)|^2$. Using such a semi-classical theory, the effective transfer coupling strengths are found from the measured transfer probabilities for each transfer channels of the nucleon. The fusion cross sections at energies below and above the barrier were then determined by incorporating these values into the coupled channel calculations. Although it was discovered that coupled-channel calculations could not replicate the enhancement in the $^{18}\text{O} + ^{116}\text{Sn}$ system without considering the neutron transfer channel, no attempt was made to find a quantitative measure of the effect of transfer on the large sub-barrier fusion enhancement observed in these systems (Deb et al., 2020). In the current work, the theoretical coupled-channels code CCFULL (Hagino et al., 1999) is used to investigate the fusion excitation function to comprehend the behavior of sub-barrier fusion in the $^{18}\text{O} + ^{116}\text{Sn}$ system.

RESULTS AND DISCUSSIONS

Fig. 1 shows the plot of the experimentally measured fusion cross sections at various energies as a function of $E_{c.m.}$. 1DBPM cross sections have been calculated to comprehend the experimental cross sections in the sub-barrier regions. To fit the cross-sections at above-barrier energies, appropriate Woods-Saxon parameterization of the nuclear potential parameters has been used for the calculations. This is because the effect of static and dynamic properties in the process of complete fusion becomes negligible in that energy range as shown in Refs. (Deb et al., 2020; Hagino et al., 1999; Stefanini et al., 2009). For the $^{18}\text{O} + ^{116}\text{Sn}$ system, the nuclear potential parameters considered in this work includes V_0 (potential depth) = 75.6 MeV, r_0 (potential radius) = 1.2 fm, and a_0 (diffuseness parameter) = 0.72 fm (Deb et al., 2020). Fig. 1 shows a plot of the computation's result. In comparison to 1DBPM fusion cross sections, it is evident that the sub-barrier region of the $^{18}\text{O} + ^{116}\text{Sn}$ system considered for this work, is enhanced. This demonstrates that the experimental fusion cross section cannot be replicated by a straightforward quantum mechanical barrier penetration model. To explain the experimental observations, basic 1DBPM computations and couplings of different inelastic states have been performed, as demonstrated in the Ref. (Deb et al., 2020). But none of the combinations could match the experimental measurements. Coupled-channels calculations, for this system, were done considering ^{18}O nucleus and ^{116}Sn nucleus as vibrators. Their contribution as a rotator is negligible as their deformation parameter values are nearly zero (Deb et al., 2020), because both the nuclei are spherical. The coupled-channels computations underestimate the fusion excitation function of the current system in the sub-barrier energy region, even after considering all low-lying inelastic excitations mutually, as shown in Ref. (Deb et al., 2020). As a result, the sub-barrier fusion boost over the coupled-channels computations might be a sign of a physical

effect that has not been considered yet. Subsequently, we needed to examine whether any neutron transfer taking place between the interacting partners could lay any role in reproducing the fusion cross-section of the present system and, therefore, could explain the sub-barrier fusion enhancement. To do this, the couplings of the neutron transfer channel have been included in coupled-channels analysis. The F_t value, as stated in the preceding section, is necessary to include transfer coupling in the coupled-channel calculations using the CCFULL software, which enables one to couple 2 neutron transfer channels only. The coupled-channel calculations are done using several values of F_t in the CCFULL code, in the 0.2 MeV to 0.5 MeV range, since the transfer cross sections have not yet been measured for the current system. Fig. 2 plots the coupled-channels calculations with +2n transfer coupling for the values of F_t in this range. From the figure, we can see the significance of the value of this parameter on the fusion cross section. Different values of F_t do not produce the same cross sections but produce different fusion cross section. Even the slight change of the value of this parameter results in substantial changes in the fusion cross section. The coupled-channels calculations are found to improve the description of experimental fusion cross sections at sub-barrier energies when F_t is increased from 0.2 to 0.5 MeV, but they significantly under-predict the fusion cross section at above-barrier energies. Below the

barrier, with the increasing value of F_t , the sub-barrier fusion enhancement increases. But again, with the increasing value of F_t , the cross section above the barrier decreases. Refs. (Khushboo et al., 2017; Sahoo et al., 2020) observed similar trends of F_t . To achieve the best agreement between the experiment and theoretical fusion excitation functions for the $^{18}\text{O} + ^{116}\text{Sn}$ system, we also included the Q value of the neutron-pair transfer channel along with the transfer coupling strength, F_t , both of which were treated as free parameters according to the prescription of Bourgin *et al.* (Bourgin et al., 2014). Thus, despite these fluctuations, Fig. 2 shows that the fusion excitation functions, with values of $F_t = 0.3$ MeV and $Q = + 4.08$ MeV, which is equal to the Q value of two neutron stripping channels for the current system, fit both below and above the barrier within the experimental uncertainties. This fitting has been displayed separately in the inset of Fig. 2 for clarity. This can be seen in Fig. 1 with the experimental cross section data since it replicates the fusion cross sections very well. Therefore, while evaluating the sub-barrier fusion enhancement, the positive Q value neutron transport routes should be considered. The comprehensive fusion and differential transfer measurements are necessary and must be carried out to provide additional insight into the role of neutron transfer channels in sub-barrier fusion enhancement.

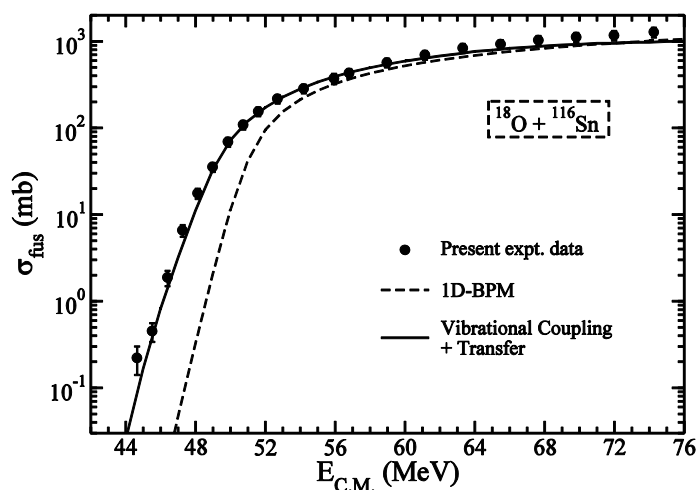


Fig. 1 The experimentally measured excitation function is compared with the 1DBPM using CCFULL. It shows that the couplings of different inelastic excitations of interacting partners in addition to the 2n transfer channel reproduces the experimental excitation function well.

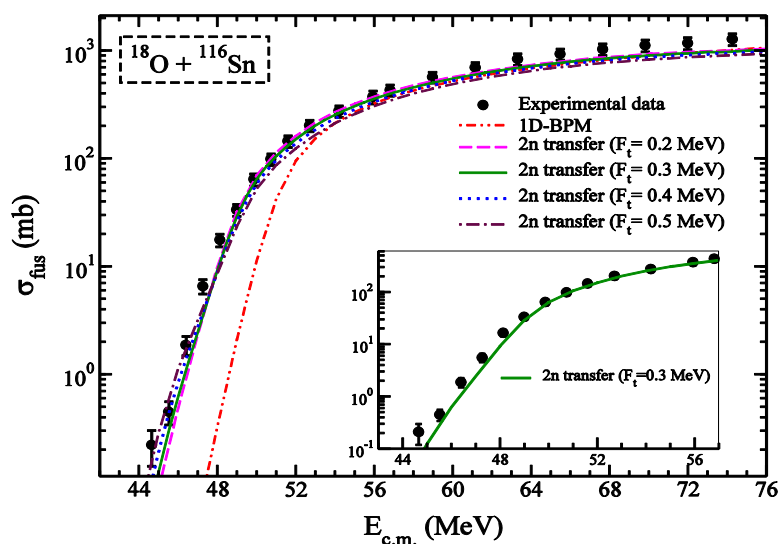


Fig. 2 The fusion excitation function is compared with the 1DBPM and the transfer coupling between interacting partners using CCFULL having various values of transfer coupling strength. It shows that the inclusion of couplings of inelastic excitations of interacting partners with 2n transfer channel having $F_t = 0.3$ MeV and $Q = +4.08$ MeV reproduces the experimental excitation function well.

CONCLUSIONS

In comparison to the straightforward one-dimensional quantum mechanical barrier penetration model, the system under consideration in this work, $^{18}\text{O} + ^{116}\text{Sn}$, has shown augmentation of the fusion cross section below the Coulomb barrier energy (Deb et al., 2020). Using the theoretical coupled channel formalism code CCFULL, coupled channel calculations were carried out, considering both ^{18}O and ^{116}Sn as vibrators, to explore the cause

of such enhancement at the sub-barrier area. Although the calculations were done with inelastic excitations of the several states of the collision partners, they were unable to replicate the experimental observations. Even when all low-lying inelastic excitations were mutually included in the calculations, the sub-barrier fusion cross section could not be replicated. For two-neutron transfer channels from the projectile to the target, the system under consideration has a positive Q value. Because

the CCFULL code allows for the inclusion of a neutron-pair transfer, calculations were done with two neutron transfer's channels. Neutron transfer coupling is done in the code using the transfer coupling strength, F_t . Transfer measurements are, therefore, desired for to determine the value of F_t . But for the present system, transfer measurements are not available. Hence, the coupled-channel calculations are considered with various trial values of F_t in the CCFULL code ranging from 0.2 MeV to 0.5 MeV, which is the main basis of this work. It was observed that while the fusion cross-section of the above barrier drops, the sub-barrier fusion cross section grows as F_t increases. The experimental findings could, thus, be replicated reasonably well throughout the entire energy regime considering $F_t = 0.3$ MeV, with the Q value of two neutron stripping channel for the current system being +4.08 MeV. Therefore, when evaluating the sub-barrier fusion enhancement, the positive Q value neutron transfer channels with the F_t value should be considered. Transfer measurements are to be done, in future, for this system to get the correct value of F_t .

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CONFLICT OF INTEREST

The author declares having no known competing financial interests or personal relationships of any form with the personnels related to the journals that could have appeared to influence the work reported in this paper. The author is not involved in the editorial review of any form or the decision to publish this article.

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Understanding Mathematical Anxiety in the Indian Scenario: A Focus on Meghalaya and Insights from Educators

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ABSTRACT

Mathematical anxiety (MA) remains a significant psychological barrier to academic achievement globally, yet its dynamics within regional Indian contexts—particularly in marginalized rural areas—remain understudied. This paper investigates the dual nature of mathematical anxiety, distinguishing between facilitative eustress and debilitating distress. Drawing upon the classic Yerkes-Dodson Law and Working Memory Theory, we introduce the Mathematical Anxiety Performance (MAP) Model and its central construct: the psychological threshold where cognitive arousal transitions from performance-enhancing to performance-impairing. To ground this model empirically, the study was conducted to present a qualitative-dominant survey of frontline mathematics educators across 13 rural secondary and higher secondary Ramakrishna Mission (RKM) schools in Meghalaya. The findings indicate that persistent underperformance on national metrics (e.g., the National Achievement Survey) is not indicative of cognitive deficits but is instead driven by systemic, pedagogical, and socio-cultural stressors that lower students' cognitive thresholds. Finally, we align these insights with the progressive, activity-based mandate of the National Education Policy (NEP) 2020, offering an integrated strategic remediation matrix to elevate the psychological threshold and foster mathematical resilience.

KEYWORDS: Mathematical Anxiety, Working Memory, Eustress, Yerkes-Dodson Law, MAP Model, Meghalaya, NEP 2020

INTRODUCTION

Mathematics is embedded in virtually every dimension of human existence and is indispensable for personal and societal development. From household budgeting to global economic modelling, from logical reasoning to technological innovation, mathematics serves as the foundational framework for understanding and navigating the world. In the educational context, teachers bear the primary responsibility of equipping students not only with mathematical competencies but also with the psychological resilience required to engage with the subject constructively. Despite its universal importance, mathematics remains among the most anxiety-inducing academic subjects across educational systems worldwide. A considerable body of literature has documented the prevalence and consequences of

mathematical anxiety (MA), a phenomenon that extends well beyond ordinary nervousness to constitute a genuine psychological barrier to learning. Richardson and Suinn (1972) were among the first to formally define mathematical anxiety as “feelings of tension and anxiety that interfere with the manipulation of numbers and the solving of mathematical problems in a wide variety of ordinary life and academic situations”. Subsequent scholars have both confirmed and expanded this definition. Tobias (1978) drew public attention to the issue by arguing that mathematical anxiety is not rooted in cognitive deficiency but in psychological conditioning, observing that many individuals who struggle with mathematics possess the intellectual capacity to succeed but are obstructed by deeply internalized fear. Contradicting the early view that anxiety is inherently debilitating, later researchers

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introduced the concept of eustress, or positive anxiety, as a functionally distinct construct. The Yerkes-Dodson Law, a foundational principle in educational psychology, posits that performance increases with mental arousal up to an optimal threshold, beyond which further arousal results in a decline. This suggests that not all forms of anxiety are harmful; moderate levels of arousal may, in fact, enhance focus and performance. Hembree (1990) confirmed through meta-analysis that while severe MA is associated with poor mathematical performance and avoidance behaviour, its relationship with performance is moderated by intensity, duration, and individual coping mechanisms. Ashcraft (2002), however, offered an important counter-perspective, demonstrating that even moderate levels of MA can impair working memory capacity, thereby degrading performance on complex mathematical tasks irrespective of the student's underlying ability. This tension between the motivating potential of mild anxiety and the debilitating effect of elevated anxiety remains a central issue in contemporary literature. Ma (1999), in a comprehensive meta-analysis, confirmed a significant negative relationship between mathematical anxiety and mathematics achievement, while simultaneously noting that this relationship is influenced by contextual variables including grade level, gender, and instructional environment. More recently, Karimi and Venkatesan (2018) found that academic hardness moderated the impact of MA on performance among Indian high school students, implying that interventions targeting psychological resilience may be as important as content-focused remediation. These findings collectively suggest that mathematical anxiety cannot be meaningfully addressed through pedagogical reform alone; systemic, psychological, and socio-cultural factors must also be considered. Within the Indian educational context, mathematical anxiety assumes salience given the high-stakes nature of the subject in academic progression and career pathways. Despite a rich mathematical

heritage, Indian students across diverse socio-economic and geographical strata consistently exhibit anxiety-related barriers to mathematical engagement. The state of Meghalaya presents a compelling regional case study. According to assessments including the National Achievement Survey (NAS), students in Meghalaya frequently perform below the national average in mathematics. Yet educators in the region consistently report that this underperformance cannot be attributed to a lack of cognitive potential, but rather to psychological, pedagogical, and systemic factors that have been insufficiently addressed by existing policy frameworks.

The present study therefore seeks to: (i) distinguish between negative and positive forms of mathematical anxiety and their respective effects on student performance; (ii) introduce the concept of a psychological threshold at which eustress transitions into debilitating distress; (iii) examine the specific manifestations and causes of mathematical anxiety within the Meghalaya context through educator insights; and (iv) propose an integrated framework, the Mathematical Anxiety Performance (MAP) Model, to guide future pedagogical and policy interventions. This paper further situates its findings within the broader aspirations of the National Education Policy (NEP) 2020 and its implications for reimagining mathematics education in India.

Theoretical Framework Anxiety: Conceptual Overview

Anxiety is a psychological and physiological state characterized by feelings of worry, nervousness, or unease, typically arising in response to a perceived threat or challenge, whether real or imagined. Anxiety can trigger physical symptoms including increased heart rate, sweating, and muscle tension, as well as cognitive effects such as difficulty concentrating or racing thoughts. In educational contexts, anxiety assumes heightened significance due to its direct interaction with academic performance and student well-being.

Anxiety may be broadly classified into two functionally distinct forms:

- i. Negative Anxiety (Distress): Occurs when anxiety becomes overwhelming, persistent, or disproportionate to the situation, leading to impaired cognitive functioning and systematic avoidance of the anxiety-inducing stimulus.
- ii. Positive Anxiety (Eustress): Produces beneficial effects on motivation, performance, and emotional well-being. A moderate level of anxiety can induce alertness, focus, and readiness to respond to challenges, which may improve performance in high-pressure situations, thereby serving as a catalyst for growth. The Yerkes-Dodson Law provides the classical theoretical basis for this distinction, illustrating that performance increases with physiological or mental arousal, but only up to a specific point,

Mathematical Anxiety: Definition and Dual Nature

Mathematical Anxiety (MA) is not a reflection of a student's mathematical ability but rather a psychological barrier that prevents them from performing to their full potential. Early conceptualizations treated MA as exclusively negative; however, contemporary scholarship recognizes a dual nature that encompasses both negative and positive forms.

Richardson and Suinn (1972) defined MA as “feelings of tension and anxiety that interfere with the manipulation of numbers and the solving of mathematical problems”. Tobias (1978) emphasized its psychological rather than cognitive origin. Ashcraft (2002) defined it as “a feeling of tension, apprehension, or fear that interferes with math performance” and demonstrated that it reduces working memory capacity. Ma (1999) described it as “a state of discomfort associated with performing mathematical tasks”, while Hembree (1990) characterized it as “an effective response to mathematics that involves fear, stress, and apprehension”. To illustrate the dual nature of MA concretely, consider three students -

beyond which further arousal becomes counterproductive (Figure 1). Anxiety, therefore, is a complex and context-dependent emotion whose impact is determined by its duration, intensity, and the individual's capacity to manage it.

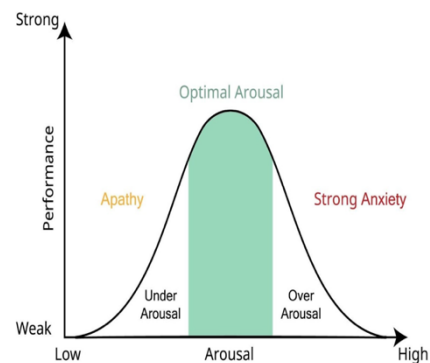


Figure 1: The Yerkes-Dodson Law illustrates the relationship between arousal levels and performance efficiency, distinguishing zones of under-arousal, optimal arousal, and over-arousal/strong anxiety.

Nikhil, Nishant, and Neelam in the same class preparing for a mathematics test. Nikhil, who dislikes the subject, experiences intense nervousness and physical symptoms such as a stomachache; upon receiving the question paper, he blanks out entirely and is unable to write. Neelam, whose favourite subject is mathematics, approaches the test with calm confidence, answers all questions thoroughly, and performs excellently. Nishant, equally enthusiastic but overconfident, becomes excessively excited, makes careless errors, forgets formulas, and underperforms relative to his ability - though he subsequently reflects on and corrects his mistakes. This scenario Figure 1 illustrates that mathematical anxiety encompasses a spectrum ranging from paralyzing fear (Nikhil) through optimal alertness (Neelam) to counterproductive overexcitement (Nishant). As the Bhagavad Gita counsels: कर्मण्येवाधिकारस्ते माफलेषु कदाचन - one has the right to perform one's actions, but not to the fruits thereof. This philosophy captures the essence of managing anxiety: focusing on process rather than outcome. This psychological distinction resonates with the

ancient wisdom of the Bhagavad Gita (Chapter 2, Verse 47), which counsels' detachment from outcomes - a mindset that, if cultivated, could itself serve as a buffer against performance-driven anxiety (Figure 4).

Negative Mathematical Anxiety

Negative Mathematical Anxiety may be defined as the emotional response that arises when an individual is confronted with mathematical tasks, characterized by intense feelings of fear, tension, and apprehension that

systematically interfere with effective mathematical performance. Its principal characteristics include Cognitive overload, wherein anxiety exhausts working memory resources, leading to poor performance even when the student possesses the requisite skills (Ashcraft, 2002). Avoidance behavior, including skipping classes, neglecting homework, and selecting academic or career pathways that minimize mathematical engagement.

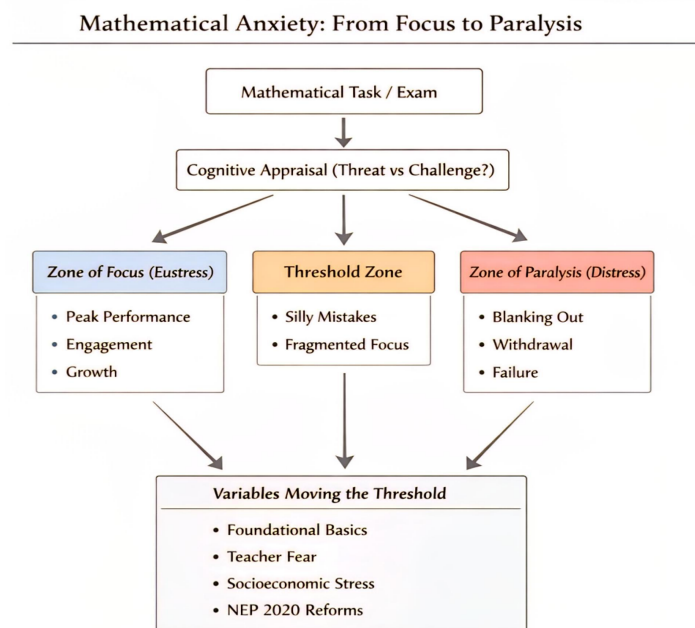


Figure 2: Conceptual model of Mathematical Anxiety pathways from focus to paralysis. Note: This figure illustrates the conceptual framework mapping student cognitive appraisals (eustress vs. distress) and the theoretical variables that modulate the psychological threshold, serving as a heuristic guide for future empirical testing

Physical manifestations such as sweating, increased heart rate, nausea, and in severe cases, panic attacks. Progressive erosion of self-confidence, creating a self-reinforcing cycle of failure and withdrawal. Long-term academic stress that impairs performance across multiple subjects.

Positive Mathematical Anxiety

Positive Mathematical Anxiety may be defined as a state of heightened alertness, motivation, and focus that arises in response to challenging mathematical tasks. Rather than impairing performance, it propels students toward

thorough preparation and sustained effort. Its key characteristics include:

Motivational drive: It encourages students to study rigorously, seek assistance proactively, and persist through difficulty. **Sharpened concentration:** It enhances focus and attentional allocation during problem-solving.

Resilience and growth: It promotes perseverance, leading to increased confidence and expanded mathematical self-efficacy.

It should be noted, however, that excessive positive anxiety may tip into overconfidence, as illustrated by Nishant, resulting in careless errors. Positive mathematical anxiety is,

therefore, optimally beneficial when maintained within a moderate range.

Probable Causes of Mathematical Anxiety in the Indian Scenario

Mathematical anxiety is a globally recognized educational phenomenon; however, its intensity and manifestation are shaped by contextual and systemic factors unique to each educational setting. In the Indian scenario, MA emerges from a complex interaction of cognitive, pedagogical, socio-cultural, and economic influences.

Cognitive and Learner-Related Factors

At the individual level, low self-confidence and weak conceptual foundations are among the most prevalent causes of MA. In India, where mathematics is widely perceived as a high-stakes subject crucial for academic progression and career opportunities, students who struggle with foundational concepts experience heightened fear of failure. The cumulative and hierarchical nature of mathematics amplifies this problem, as early conceptual gaps persist and compound across higher grades. Poor concentration, often exacerbated by large class sizes and limited individualized attention, further hinders mathematical comprehension. Rote-based learning approaches which emphasize procedural memorization over conceptual understanding restrict adaptive problem-solving and increase anxiety during examinations.

Pedagogical and Teacher-Related Factors

Teachers occupy a central role in shaping students' affective and cognitive relationships with mathematics. In the Indian context, variations in pedagogical training, classroom practices, and institutional cultures significantly influence learning outcomes. Mismatch between classroom instruction and homework difficulty wherein simpler problems are demonstrated in class while more complex tasks are assigned without scaffolding contributes to student frustration and self-doubt. The quality of the teacher-student relationship also plays a critical role: supportive and encouraging teachers can substantially mitigate MA, whereas dismissive or

authoritarian approaches may intensify avoidance behaviour. The prevalence of private tuition culture in India further stratifies learning opportunities. Students who cannot afford supplementary coaching may receive less individualized instruction, contributing to performance gaps, diminished self-esteem, and heightened anxiety.

Family and Home Environment Factors

Family background significantly mediates students' mathematical experiences. Limited parental involvement - frequently a consequence of occupational demands restricts the academic guidance available at home. Moreover, parents who themselves experience MA may unconsciously transmit negative mathematical attitudes to their children, perpetuating intergenerational cycles of anxiety. Conversely, excessive parental pressure for high academic achievement, particularly common in competitive Indian households, may similarly heighten MA.

Socio-Economic Influences

Socio-economic disparities are particularly pronounced in the Indian educational landscape. Students from economically disadvantaged backgrounds often face financial stress, constrained access to learning resources, and unstable home environments all of which negatively affect cognitive functions including attention, memory, and problem-solving capacity. In some communities, school attendance is motivated primarily by welfare programmes (such as the Midday Meal Scheme) rather than academic aspiration, which may reduce engagement with mathematically demanding subjects.

Classroom, Social, and Cultural Factors

The examination-oriented culture prevalent in Indian classrooms characterized by ranking, performance pressure, and public evaluation intensifies MA, particularly in a subject where errors are highly visible. Societal stereotypes, including the persistent belief that boys possess an inherent advantage in mathematics, negatively affect the self-perception and mathematical confidence of female students,

discouraging participation and reinforcing anxiety despite equal cognitive potential.

Systemic and Policy-Level Factors

At the systemic level, gaps in teacher training and professional development, inequitable distribution of educational resources, and assessment frameworks that prioritize summative over formative evaluation contribute to MA. While the National Education Policy (NEP) 2020 explicitly emphasizes conceptual understanding, experiential learning, and reduced rote memorization, effective and uniform implementation across diverse regional contexts remains a significant challenge.

The Psychological Threshold

The “Threshold” represents the critical psychological and physiological tipping point at which Positive Mathematical Anxiety (eustress) transitions into Negative Mathematical Anxiety (distress). Drawing upon the Yerkes-Dodson Law, the threshold is the point on the arousal-performance curve at which additional anxiety ceases to be facilitative and begins to impair cognitive functioning. The psychological threshold is operationally defined using the Working Memory Theory, which posits that human beings have a cognitive system with a limited capacity responsible for temporarily holding and manipulating information necessary for complex tasks such as reasoning, comprehension, and learning. Think of working memory as the “mental workspace” or RAM of your brain. It can only hold a few pieces of information at once. When a student solves a math problem, their working memory is actively managing numbers, recalling formulas, and processing steps all at the same time.

According to this theory, the psychological/cognitive threshold is defined as the exact point where a student’s limited working memory capacity becomes completely overwhelmed. It can be expressed through a simple cognitive balance equation:

Threshold = Available Working Memory Capacity - (Task Cognitive Load + Anxiety-Induced Intrusive Thoughts)

The three student archetypes introduced earlier map directly onto positions relative to this threshold framework:

Below the Threshold (Optimal Performance): When a student is focused and experiences mild excitement or alert readiness (eustress), their working memory is entirely dedicated to the math task itself. Neelam represents the optimal zone.

At the Threshold (The Tipping Point): As anxiety increases, the brain begins to generate intrusive, negative thoughts (“I’m going to fail”, “I’m not smart enough”). These thoughts start competing with the math problem for space in the working memory. The student begins making careless, silly mistakes because their mental workspace is getting crowded. Nishant illustrates the threshold zone. **Beyond the Threshold (Cognitive Paralysis):** The threshold is officially crossed when the anxiety-driven thoughts and physical panic consume so much working memory space that there are virtually no cognitive resources left to process the actual mathematics. Even if the student is entirely capable of solving the problem, their mental workspace is completely hijacked by fear, leading to “blinking out” or total performance paralysis. Nikhil represents the paralyzing zone. Ashcraft (2002) provides the neuropsychological basis for this model, demonstrating that anxiety-related intrusive thoughts occupy working memory capacity that would otherwise be available for mathematical computation. The threshold is therefore operationally defined as: The point at which anxiety-related cognitions (fear of failure, negative self-evaluation) consume a greater proportion of working memory than the mathematical task itself, rendering effective performance impossible.

Mathematical Anxiety in Meghalaya: Insights from Educators

The state of Meghalaya presents a distinctive regional context for examining mathematical anxiety. According to multiple assessments including the National Achievement Survey (NAS), students in Meghalaya frequently perform below the national average in

mathematics, and a substantial proportion fail to meet expected grade-level competency benchmarks. Concurrent government education policies have, in several respects, inadequately supported the genuine learning outcomes required in the subject.

Crucially, educators throughout the state consistently assert that this pattern of underperformance does not reflect an inherent cognitive deficit in Meghalaya students. Rather, multiple intersecting external factors pedagogical, systemic, socio-economic, and psychological conspire to generate elevated and persistent mathematical anxiety. The following analysis draws upon qualitative insights gathered from mathematics teachers across 13 Ramakrishna Mission schools in the state.

METHODOLOGY

Study Design and Rationalized Institutional Selection

The present investigation adopts an exploratory descriptive survey design with a qualitative-dominant approach. This methodology is specifically selected to investigate the systemic, environmental, and affective dimensions of mathematical anxiety through the expert lens of frontline educators. Rather than executing a broad, non-specific macro-survey across well-resourced urban centres, this study purposefully deploys an intensive regional focus on the Ramakrishna Mission (RKM) school network. In Meghalaya, a stark educational divide exists between urban centres like Shillong, which benefit from concentrated institutional infrastructure, robust learning resources, and stable pedagogical environments and remote rural sectors characterized by unique systemic vulnerabilities. RKM schools serve as a critical educational lifeline in these underserved rural regions. While the RKM network spans numerous primary and exploratory learning centres throughout the state, this study purposefully isolates institutions operating strictly at the Secondary and Higher Secondary school levels. This specific institutional constraint was established because formal mathematical anxieties, abstract problem-solving demands, and high-stakes evaluative

pressures peak during these specific developmental years. This targeted institutional focus narrowed the eligible pool to 13 core regional schools:

RKM Secondary School, Ladmawphlang
RKM Secondary School, Laitlyngkot
RKM Higher Secondary School, Nartiang
RKM Higher Secondary School, Nongwar
RKM Higher Secondary School, Shella
Ramakrishna Mission, Sohra
RKM Secondary School, Kalibari
RKM Secondary School, Swer
RKM Secondary School, Laitlyndop
RKM UP School, Nongkynrih
RKM Higher Secondary School, Myllem
Ramakrishna Mission, Mawmluh
RKM Higher Secondary School, Sohbar

Participant Characteristics

The sample consists of 15 frontline mathematics educators dedicated to these targeted regional institutions. While the resulting numerical sample size of teachers is bounded, the cohort represents an exhaustive, targeted capture of secondary-level mathematics faculty across these rural networks. Among the participants, 13 provided full demographic profiles, revealing an age distribution ranging from 24 to 52 years, a gender composition of 10 male and 3 female instructors, and professional instructional expertise spanning from 1 to 22 years; the remaining 2 educators participated anonymously, leaving their specific names, genders, and ages unrecorded.

The methodological decision to gather data primarily from educators rather than directly from students is a deliberate strategy designed to capture a consolidated, high-fidelity diagnostic view of student anxiety. Frontline mathematics teachers in rural settings do not merely observe single exam outcomes; they function as experienced, long-term expert informants. Their professional perspectives represent a synthesized accumulation of daily classroom interactions, student behavioural patterns, localized parental dynamics, and continuous diagnostic assessments. By tapping into this aggregated educator experience, the

study bypasses the immediate performance biases or transient test-day panic that often skews direct student surveys, yielding instead a robust structural overview of how mathematical anxiety manifests continuously in rural environments.

Data Collection

Data were collected through structured questionnaires and semi-structured interviews designed to triangulate the systemic triggers, observable behaviours, and threshold variables modulating student anxiety.

RESULTS

Survey Findings

Analysis of the survey data yielded the following key findings across three thematic domains:

Causes of Mathematical Anxiety Identified by Educators:

Weak foundational knowledge: 70% of educators identified this as a primary contributing factor. Lack of parental support: Cited by 60% of respondents. Gender stereotypes in mathematics: Noted by 45% of educators.

Common Student Responses to Mathematical Anxiety:

Fear of failure: Reported by 85% of educators as the dominant student response. Avoidance of mathematics: Observed by 65% of respondents. Performance pressure: Noted by 50% of educators.

Recommended Interventions:

Use of innovative and varied teaching aids: Endorsed by 75% of educators. Reformed and formative assessment methods: Recommended by 80% of respondents. Greater parent-teacher collaboration: Advocated by 65% of educators.

Educator Voices

Qualitative analysis of educator interviews revealed consistent and substantive concerns regarding structural barriers to mathematical learning in Meghalaya. Educators highlighted challenges including overcrowded classrooms, inadequate infrastructural facilities, salary disparities between institutional categories, and insufficient opportunities for professional

development as significant impediments to effective mathematics teaching.

A recurrent theme in educator accounts was the role of conditioned belief systems in generating and sustaining mathematical anxiety. As one educator observed, “the biggest challenge is not the students’ ability, but their mindset. They have been conditioned to believe that mathematics is difficult, and this belief becomes a self-fulfilling prophecy”. Such observations align closely with Ashcraft’s (2002) account of how anxiety-driven intrusive thoughts displace mathematical cognition from working memory.

Threshold Factors: Research Evidence

Based upon the integrated analysis of survey data and qualitative insights, the following factors were identified as those that systematically lower the psychological threshold, rendering students more vulnerable to crossing from eustress into debilitating distress:

Weak Foundational Knowledge (70%): The absence of basic conceptual competence means that even modest task demands can trigger the threat response, consistent with Ashcraft’s (2002) account of MA’s impact on working memory.

Environmental Stressors: Overcrowded classrooms and the absence of individualized support reduce students’ cognitive buffering capacity against anxiety.

Socioeconomic Pressure: Chronic baseline stress arising from economic disadvantage lowers the threshold for academic anxiety, leaving fewer cognitive resources available for mathematical engagement.

Fixed Mindset: Educators noted that students conditioned to regard mathematics as inherently inaccessible experience threshold collapse at the earliest sign of difficulty, consistent with Dweck’s (2006) growth mindset framework.

Mathematical Anxiety Performance (MAP) Model: A Cognitive-Behavioural Framework

Building upon the exploratory findings obtained from the rural Meghalaya RKM

school network and the cognitive-threshold perspective developed in this study, a Mathematical Anxiety Performance (MAP) Model is proposed as a conceptual framework for explaining the relationship between anxiety and mathematical performance. Positioned prior to the broader discussion of regional educational dynamics, the model provides a foundational structure for understanding how systemic and psychological factors translate into observable student behaviours and academic outcomes. The MAP Model conceptualizes mathematical performance as a function of cognitive arousal and identifies three distinct operational zones along an anxiety-performance continuum (Figure 3).

Engagement Zone (Eustress)

The Engagement Zone represents an optimal level of psychological arousal where students experience productive stress that enhances concentration, motivation, and mathematical engagement. Within this zone, anxiety functions as a facilitating factor rather than an impediment, enabling students to remain focused and resilient when confronted with mathematical challenges. Students operating in this area demonstrate behavioural characteristics like the Neelam archetype, effectively transforming moderate stress into sustained academic effort and successful task execution.

Warning Zone (Cognitive Threshold)

The Warning Zone is situated at or near the critical cognitive threshold where levels of arousal begin to compromise performance. Although students in this zone retain the capacity to solve mathematical problems, their cognitive stability becomes increasingly fragile. Consistent with the Nishant archetype, these learners are susceptible to concentration lapses, excessive excitement, procedural inaccuracies, and avoidable mistakes.

Performance remains possible, but the probability of error increases substantially due to the growing burden on working memory resources.

Paralysis Zone (Distress)

The Paralysis Zone reflects a state of severe mathematical anxiety in which cognitive and emotional demands exceed an individual's coping capacity. At this stage, working memory resources become overwhelmed, resulting in marked cognitive impairment. Students exhibit behaviours represented by the Nikhil archetype, including task avoidance, mental shutdown, inability to retrieve previously learned knowledge, and failure to execute mathematical procedures despite possessing the underlying intellectual capability to do so.

Dynamic Nature of the Cognitive Threshold

A central proposition of the MAP Model is that the cognitive threshold is not fixed but is continuously influenced by environmental, academic, and psychosocial factors. Evidence from educator survey responses indicates that several structural liabilities operate as negative vectors that lower the threshold at which anxiety begins to impair performance. These include foundational mathematical deficiencies (reported by 70% of educators), environmental and school-related stressors, localized socioeconomic pressures, and entrenched fixed-mindset beliefs regarding mathematical ability. Conversely, the MAP Model incorporates targeted intervention mechanisms designed to strengthen coping capacity, protect working memory resources, and elevate the cognitive threshold. Such interventions aim to reduce the adverse effects of mathematical anxiety and facilitate the systematic movement of students back toward the Engagement Zone, where optimal learning and performance are most likely to occur.

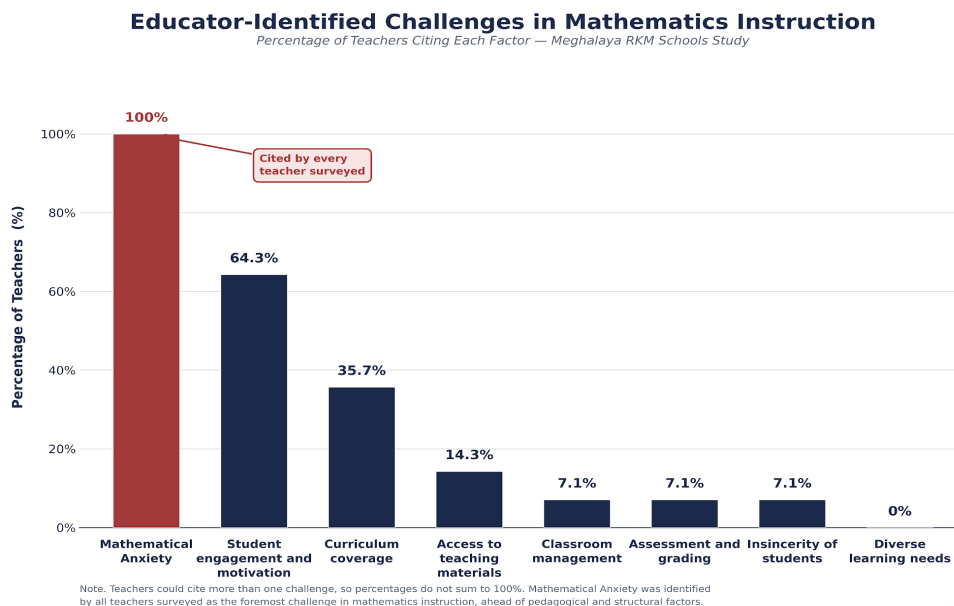


Figure 3: Survey results from regional educators highlighting the percentage distribution of the biggest instructional and structural challenges faced within the mathematics classroom

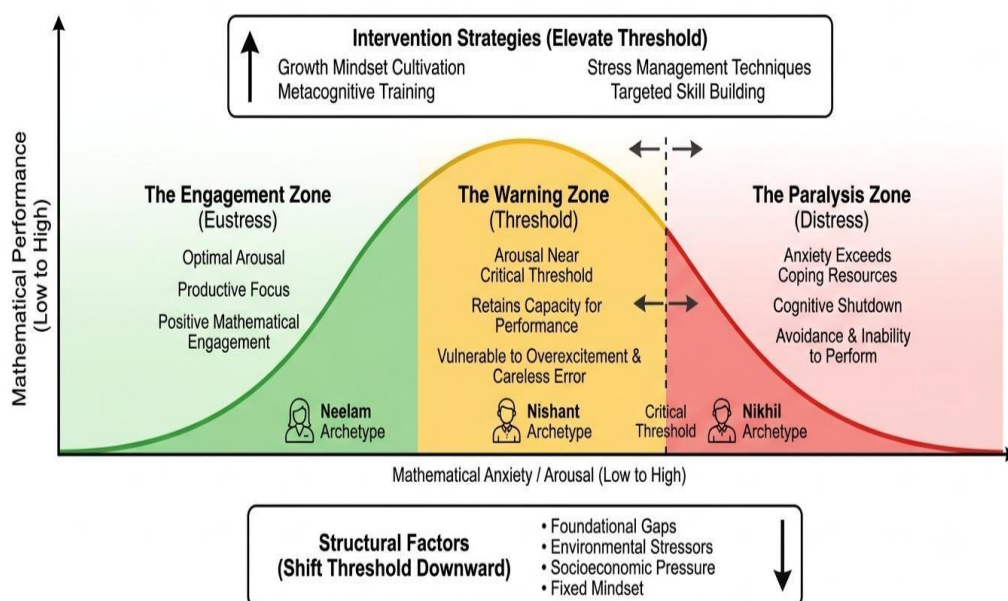


Figure 4: The Mathematical Anxiety Performance (MAP) Model mapping student behavioural archetypes (Neelam, Nishant, and Nikhil) along the cognitive threshold of the mathematical anxiety-arousal curve.

DISCUSSION The qualitative-dominant findings gathered from frontline educators in rural Meghalaya highlight that student underperformance on macro-metrics such as the National Achievement Survey (NAS) is fundamentally an affective and structural

problem rather than an inherent cognitive deficit. When the MAP model is applied to these field realities, it becomes clear that rural students frequently experience threshold collapse at a much earlier stage of mathematical engagement than their urban counterparts. The

systemic lack of foundational mathematical knowledge, cited by 70% of the surveyed teachers, means that even routine secondary-level problem solving is appraised by the student as an overwhelming threat rather than a manageable challenge. When this baseline conceptual vulnerability is compounded by remote environmental constraints such as overcrowded classrooms, limited visual teaching aids, and minimal parental academic support, the cognitive space required to buffer anxiety is severely depleted. This baseline distress systematically hijacks working memory capacity, causing students to cross the

psychological threshold into the Paralysis Zone before they can even apply their actual cognitive potential to a task. Addressing this regional anxiety cycle requires transitioning away from content-heavy, high-stakes evaluative methodologies toward low-stakes, formative frameworks that actively protect the student's affective state. To bridge the gap between structural policy and classroom realities, this study proposes below in tabular form, an integrated framework of action across pedagogical, psychological, environmental, and policy dimensions:

Pedagogical & Confidence Building	Environmental Support	Practice & Mindset
Remedial classes & structured logical progression from simpler to highly complex tasks.	Cultivate a warm, positive classroom attitude; actively reduce stigma associated with errors.	Integrate additional scaffolded support during available instructional periods.
Use concrete visual models, tactile aids, and localized physical representations.	Initiate early, accessible mathematical problems to build confidence & intrinsic motivation.	Encourage daily conceptual clarification & continuous professional teacher development.

This strategic framework directly aligns with the National Education Policy (NEP) 2020, which offers a critical structural lever to elevate the psychological threshold. By replacing rote memorization with activity-based exploration, mathematical games, and experiential learning, the policy reduces the threat valence associated with errors. When a classroom culture actively normalizes mistakes as essential diagnostic steps in the learning process, the student's threshold for paralysis rises, enabling extended, constructive performance within the Engagement Zone. While this study offers valuable insights into the affective landscape of regional mathematics education, certain contextual boundaries must be explicitly acknowledged:

Indirect Nature of Student Metrics: Because the diagnostic data is derived from the expert viewpoints of educators, the student performance and psychological indicators are interpreted through an instructional lens rather than measured directly from the student cohort. Future empirical investigations should aim to

pair these educator reflections with direct student psychometric profiling.

Sample Size and Geographic Scope: The sample is explicitly drawn from 13 specific secondary-level RKM schools operating within rural terrains. Consequently, the statistical sample size remains naturally bounded, and the findings cannot be generalized to well-resourced urban settings, such as downtown Shillong, where educational infrastructures differ dramatically. However, this sample serves as a highly targeted, ecologically valid representation of the rural-educational realities it intended to isolate.

CONCLUSIONS

This study demonstrates that mathematical anxiety is a dynamic, context-dependent barrier rather than an immutable cognitive limitation. By introducing the dual-nature concept of anxiety and the psychological threshold framework through the MAP Model, this paper provides a field-valid, actionable lens to evaluate student performance in vulnerable educational landscapes. While the present work

introduces the MAP model as a conceptual framework meant to guide future empirical research, it highlights the urgent need for localized, qualitative realities to inform macro-level educational policies. Successful implementation of the experiential mandates of NEP 2020 supported by equitable systemic resource distribution to rural sectors holds the potential to eliminate performance paralysis and foster genuine mathematical confidence across diverse student demographics.

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CONFLICT OF INTEREST:

The author declares no conflict of interest.

ETHICS STATEMENT:

This study was conducted in accordance with ethical principles for social science research. Participation was voluntary, and data were collected with the informed consent of all participants.

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Exploring Holistic Development through Service-Learning: An Interpretative Phenomenological Analysis of Student Experiences

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ABSTRACT

Service-learning is widely recognised as a pedagogical approach that integrates academic learning with community-based engagement and structured reflection (Bringle & Hatcher, 1996; Eyler & Giles, 1999). Because service-learning is grounded in experiential and transformative learning processes, and because Interpretative Phenomenological Analysis (IPA) is particularly well suited to illuminating how individuals make sense of significant lived experience, this study employed IPA to examine how university students experience and interpret holistic growth through service-learning. Three undergraduate students at Assam Don Bosco University (ADBU) were purposively selected and engaged in in-depth interviews exploring the intellectual, moral, social, and identity-related (spiritual) dimensions of their development. Analysis followed established IPA procedures, generating personal experiential themes within each case and group experiential themes across cases. The findings show that holistic development through service-learning is not a linear outcome of participation, but a dynamic, interpretative process shaped by students' reflective engagement with real-world challenges. The analysis further identifies a recurring tension between institutional structures, such as hour-based requirements and grading systems and students' pursuit of genuine, internally motivated engagement. The study concludes that service learning is most likely to support holistic development when institutional frameworks prioritise structured reflection — deliberately facilitated opportunities for students to process and interpret their experience and student ownership, rather than procedural compliance alone.

KEYWORDS: service-learning; holistic development; interpretative phenomenological analysis; lived experience; higher education

INTRODUCTION

Universities have historically been conceived not merely as sites of knowledge transmission but as institutions responsible for shaping the intellectual and moral character of future citizens (Dewey, 1938). In contemporary India, this formative role has been explicitly foregrounded within the National Education Policy (Ministry of Education, 2020), which emphasises holistic development encompassing intellectual competence, ethical reasoning, social responsibility, and purposeful living. The University Grants Commission (UGC, 2022) has further operationalised this vision by recommending structured community engagement and service-learning as integral to

student formation. Service-learning is broadly understood as a pedagogical approach that integrates academic learning with community-based engagement and structured reflection that is, deliberately guided opportunities for students to process, analyse, and derive meaning from their experience, rather than simply complete it (Ash & Clayton, 2009; Bringle & Hatcher, 1996; Eyler & Giles, 1999). The model draws from experiential learning theory (Kolb, 1984), which posits that knowledge emerges through cycles of experience and reflection, and is frequently linked with transformative learning theory (Mezirow, 1991, 2000), which highlights the

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potential for perspective transformation through disorienting or unexpected experiences. Empirical research demonstrates that service-learning participation is associated with increased civic engagement, empathy, and academic development (Celio et al., 2011; Yorio & Ye, 2012). However, much of this research is grounded in outcome-based or survey-driven designs, leaving underexplored the subjective processes through which students interpret and internalise their growth. While service-learning research often emphasises measurable outcomes, fewer studies have examined the qualitative learning processes that shape how students make sense of their experiences (Choi et al., 2023; Kiely, 2005). The study of holistic development through service-learning in India remains limited, as existing research has largely centred on Western contexts, with Asian and particularly Indian settings remaining underexplored (Choi et al., 2023; Salam et al., 2019). Questions such as how students understand intellectual growth beyond academic performance, how they navigate moral complexity in lived contexts, how relational engagement reshapes their sense of self and how service-learning influences existential reflection on purpose and responsibility are central to understanding holistic growth. These questions require methodological approaches capable of exploring students' lived experiences in depth. This study employs Interpretative Phenomenological Analysis (IPA) to explore how students experience and interpret holistic growth through service-learning engagement. Rather than assuming growth as a direct outcome of participation, this study investigates how growth is interpreted, negotiated, and internalised in narrative form. The research question guiding this study is: How do students experience and interpret holistic growth through their service-learning engagement. The objectives of the study are as follows:

- i. To explore the lived experiences through which university students construct and make sense of holistic development during service-learning engagement.

- ii. To examine how students experience and interpret their intellectual, moral, social, and personal growth during service-learning.
- iii. To understand these processes through the interpretative, idiographic lens of Interpretative Phenomenological Analysis (IPA).

METHODOLOGY

This study adopted Interpretative Phenomenological Analysis (IPA) as its methodological framework. Given the focus on holistic growth as lived experience rather than measurable outcome, IPA was well suited to the study, its commitment to understanding how individuals make sense of significant experiences, combined with its idiographic orientation, allowed the analysis to prioritise depth and detailed case engagement over breadth (Smith et al., 2022; Smith & Nizza, 2022). **Participants and Sampling.** The study was conducted at Assam Don Bosco University (ADBU), where service-learning has been institutionalised since 2021. Participants were selected through purposive sampling, whereby the university's Service-Learning Officer referred prospective participants based on three criteria: active and consistent participation in service-learning activities, willingness to participate in research, and a minimum of 100 hours of service-learning experience. The twenty individuals on this referred list were contacted, met in person, and informed both verbally and in writing about the purpose, procedures, and voluntary nature of the study; written informed consent was obtained from each participant before the interview proceeded. For the purposes of this article, three participants who completed in-depth interviews are reported, assigned the pseudonyms Sharon, Amy, and Manoj to protect their identities. This small, purposively selected sample is consistent with IPA's idiographic focus, which requires careful, time-intensive engagement with each case rather than breadth of coverage (Smith et al., 2022; Smith & Nizza, 2022).

Data Collection

Data were collected through an in-depth interview, with each interview lasting approximately 50 to 60 minutes. Interviews were audio-recorded and transcribed verbatim. Transcripts were returned to participants by email for member-checking, giving them the opportunity to verify accuracy and add or clarify information before analysis proceeded.

Data Analysis

Analysis followed established IPA procedures (Smith et al., 2022; Smith & Nizza, 2022). Each transcript was read and re-read to develop familiarity with the participant's account. Exploratory notes were produced to capture descriptive content, language use, and early interpretative ideas. These notes were then developed into Personal Experiential Themes (PETs) within each case, and connections across PETs were examined to construct a coherent thematic structure for each participant. After completing this process for all three participants, patterns of convergence and divergence were examined across cases to develop Group Experiential Themes (GETs).

Reflexivity and Trustworthiness

Reflexivity was treated as integral to the analytic process, consistent with IPA's double hermeneutic, in which the researcher interprets participants' own interpretations of their experience (Smith et al., 2022). The researcher's familiarity with ADBU's institutionalised service-learning programme provided valuable contextual but also required deliberate bracketing of prior assumptions about the programme's potential outcomes during interviewing and analysis. This helped ensure that the participants' meanings and perspectives remained central to the interpretation of the data. Where the researcher's interpretation extends beyond what was explicitly stated by participants, this was identified in the findings as interpretative commentary rather than direct report. Trustworthiness was addressed in accordance with Levitt et al.'s (2018) reporting criteria for qualitative research. Consistent with IPA, the study employed a small, purposively selected homogeneous sample to facilitate an in-depth

exploration of participants' experiential meaning-making. Data were generated through an interview guide, audio-recorded, transcribed verbatim, and reviewed through member-checking to ensure accurate representation of participants' experiences.

Analysis followed established IPA procedures, including exploratory noting and the development of Personal Experiential Themes (PETs) and Group Experiential Themes (GETs). Findings are presented with contextualised verbatim quotations to enable readers to evaluate the interpretations in relation to the underlying data (Smith et al., 2022).

Ethical Considerations

This study was conducted in accordance with the ethical principles governing research with human participants. Institutional permission for data collection was obtained from Assam Don Bosco University prior to the commencement of the study. On the strength of this authorisation, the researcher approached the university's Service-Learning Officer with a request to refer prospective participants meeting the study's criteria, from whom the list of participants reported in this article was subsequently drawn. Within this institutional authorisation, all participants were informed of the purpose and procedures of the study, as well as the voluntary nature of their participation. Written informed consent was obtained from all participants prior to data collection. They were assured of confidentiality and anonymity; pseudonyms (Sharon, Amy, and Manoj) are used throughout and identifying institutional and personal details have been omitted or generalised where they could compromise anonymity. Participants were also informed of their right to withdraw from the study at any stage without consequence to their academic standing and all audio recordings and interview transcripts were stored securely and were accessed for research purposes only.

RESULTS

The findings presented below integrate interpretative commentary with verbatim excerpts from participants, ensuring that interpretations remain grounded in and

accountable to the participants' lived experiences.

Theme 1: From Classroom Knowledge to Real-World Meaning

The participants described service-learning as fundamentally changing how they understood academic knowledge. Ideas that felt abstract or theoretical in the classroom became more tangible and purposeful when applied in real community situations. This shift also required participants to recognise the limitations of their prior understanding, adapt their communication, and take responsibility in the field. Sharon's experience illustrates how classroom learning became practical through entry into community settings. She describes service-learning as both a curricular requirement and an opportunity for field engagement, where knowledge had to be applied directly: "To me, it is a part of a curriculum, yes, but I also see it as community engagement, getting to work in the field, because it has provided us some opportunities to actually go to the field and apply some of our knowledge..." This applied engagement also led her to re-examine previously held assumptions. Rather than feeling confident in prior knowledge, she describes learning through correction: "when I started looking into the topic in a deeper way... realized that how wrong I was about those topics, and I actually got to learn many new things through that." In Sharon's account, learning became more meaningful because it required both application and critical self-reflection.

Amy's account foregrounds learning through discomfort and unfamiliar challenge. Her experience with career counselling and crowdfunding placed her in an exposed and demanding role. She describes the experience as both unsettling and generative: "I never thought I could be comfortable asking people for money... but then, there I was forced to do it. And on doing it, I realized that I made myself vulnerable, I let myself be out there." Over time, this experience also shifted how she conceptualised education. She began to understand learning as extending beyond

academic content into real-life tasks and personal development: "Education is so much more than that, it's when they say holistic development of a child, there are no boundaries to education." Amy's account suggests that applied engagement changed not only what she did, but how she understood the very purpose of learning itself.

Manoj's narrative reveals that applied engagement is also constituted through relationships and belonging. He describes the meaning he found in service-learning through the children's responses to the team's presence: "When the children used to come and play with us, they used to say in their local dialect like 'dada agaya, dada agaya' (brother is coming) ... so like we used to feel happy..." This recognition mattered because it signalled connection and acceptance. He describes this as a form of bonding: "It gave me a sense of bonding with them, and they also used to call us..." For Manoj, the meaningfulness of learning was inseparable from the relational quality of engagement.

Across participants, academic learning became more meaningful when classroom knowledge was applied in real situations, when prior assumptions were corrected through experience, and when participants witnessed the tangible impact of their engagement on others.

Theme 2: From Moral Certainty to Contextual Judgement

Across participants, service-learning did not simply reinforce pre-existing moral positions; rather, it introduced moments of ethical complexity that unsettled simplistic understandings of right and wrong. Their experiences also exposed the gap between theoretical ideals and lived structural realities. Through this friction, participants developed a more reflexive and context-sensitive moral awareness.

Sharon's reflections reveal an emerging sense of moral responsibility tied to her evolving professional identity as an educator. She articulates an ethical principle grounded in epistemic accountability: "Since I will be a

future educator, I want to impart the knowledge to more students that are accurate and true... But do not trust my words, you go back search on the topic and see if what I have said is correct or not, because as an educator, it is my responsibility to bring good foundational knowledge to the students..." Here, moral responsibility is framed not as authority but as accountability. Knowledge must be accurate, but equally open to independent verification. However, this principled stance becomes ethically complicated in practice, revealing a further layer of moral complexity: beyond the accuracy of the information conveyed, Sharon also had to attend to how that information was received. While conducting sessions on menstruation, she recalls: "I would sometimes notice the girls being very uncomfortable... I used to feel guilty inside.

But then it was also important that they knew about those things... I have done my part, yes, but I have not actually completely done my part... it was kind of just doing it for the sake of it." Her moral conflict lies between causing discomfort and providing necessary knowledge. The absence of meaningful follow-up lingers as unresolved responsibility. Amy's account foregrounds moral ambiguity even more explicitly. She describes a clash between right and wrong when observing teachers confiscating Rubik's Cubes: "according to them... it is wrong because it is a distraction. However, if you look at it from a different perspective, it may not entirely be wrong... Is it always necessary... to think of things as right or wrong?" The binary collapses under contextual interpretation. Amy returns repeatedly to the instability of moral categorisation: "what is right for me may not be right for others... what's right and what's wrong doesn't have to be absolute... it is subjective." This questioning deepens during classroom management challenges: "I thought if I had content... they would listen. But it was actually not like that... So is it necessary for me to scream at them... because for me, that would not be ethically right... So, is it okay for me to use force..." Her dilemma is not theoretical; it is embodied and

immediate. Ethical idealism confronts pedagogical reality. Similarly, when children raise questions about discrimination and LGBTQ identity, Amy hesitates: "there was so many things there that I wanted to share, but I held back... what if ... according to the parents, what if it's ethically wrong?" Moral expression here is no longer individual conviction; it is negotiated within institutional and community structures. Ethical action is constrained by context.

Manoj's reflections extend moral analysis into structural terrain. While maintaining that "whatever is right, is right," he acknowledges that theory frequently fails under real-life conditions: "From the theories that we learn in our classroom, there are always like loopholes like in real life... that is a good theory... but in reality, there is time constraint, there is financial stress, family stress..." His observation of an Anganwadi Centre illustrates the gap between policy and practice: "...according to government standards should be at least two rooms... and they should provide mid-day meals... But it was a small room... the midday meal... she used to prepare it at home... on paper, it seems seamless... but when it comes to the ground reality..." The moral discomfort here is structural rather than personal. Ideals exist and policies exist, yet implementation depends on individual adjustment and improvisation. Manoj concludes that responsibility cannot rest solely on government initiatives; people must also "initiate themselves." His moral reasoning thus expands from individual action to collective and structural responsibility.

Across the three accounts, moral development emerges not as the reinforcement of existing values but as the destabilisation of moral certainty. Sharon experiences guilt and a sense of incompleteness. Amy confronts the limits of absolute moral categories. Manoj recognises structural constraints that complicate theoretical ideals. Together, their narratives suggest that ethical awareness deepens precisely when good intentions encounter discomfort, ambiguity, and systemic limitation.

Moral growth, in this sense, is born from friction between ideals and practice, conviction and context, policy and lived reality.

Theme 3: From Student to Contributor

Across participants, service-learning did not merely expand skillsets; it appeared to consolidate identity. Through recognition from the community and lived responsibility in unfamiliar roles, participants began to understand themselves differently not only as students fulfilling a requirement, but as emerging professionals, contributors, and moral agents. Affirmation from others and the assumption of responsibility worked together to stabilise and strengthen their evolving sense of self.

Sharon describes service-learning as giving her a future-oriented sense of direction: "...it has actually kind of given me something to look for, which is kind of like a vision of my own... to see myself how I want myself to be in the future... it has kind of somehow strengthened some of my values and principles in life that I have." Service-learning functions here as a reflective mirror through which she imagines herself as educator, person, and community member. Her developing professional identity is further reinforced through recognition from students: "ma'am, are you coming back next Saturday?... please do not forget us... it would make me feel good, that okay, at least what I have done has affected in some ways." This affirmation validates her presence and impact. Recognition from community members translates into internal confidence: "it ... gave me that confidence... given me the courage to take steps... leading my group... explain to the community people... this needs a lot of courage... come up out of my shell." The repeated emphasis on "courage" suggests that identity consolidation here involves actively overcoming self-limiting beliefs. She no longer understands herself as someone who "cannot do that," but as someone capable of occupying professional and relational spaces.

Amy's account reflects a more expansive reconfiguration of identity. She describes service-learning as dynamic and purpose-

renewing: "if I have to do something, it has to be evolving every day... the world has endless opportunities... Service-Learning... rekindle that purpose in me." She frames her growth as a clear before-and-after shift: "Before Service-Learning and after Service-Learning, I was a totally different person... you take things out of the textbook... through those inter human interactions... you will undergo changes." Through relational engagement with teachers, she also reconstructs her understanding of the teaching profession: "teaching is not just physical... it's mental, it's emotional, it's psychological, and... even spiritual... we have to also understand that they're also being pressurized from the higher authorities." Recognition operates here not merely through student affirmation, but through relational understanding of structural pressures. Her identity expands from self-focused academic performer to socially aware participant: "...before Service-Learning my mind was very limited to only myself... but after... I realized that every one of us have this potential to do something for the society... my life is not only meant to be lived only for me." Identity consolidation, for Amy, involves a fundamental outward reorientation: responsibility for others becomes part of how she now understands and defines herself.

Manoj's reflections centre on recognition through relational belonging. Initially uncertain whether community members would engage with the team, he found: "If we initiate... people are welcoming..." The repeated greeting "Dada has come, dada agaya" functions as acknowledgment from the community: "when we went for home visits, people used to welcome us... bring out their chairs..." These gestures indicate social acceptance and belonging; he is no longer an outsider performing a task, but someone expected and valued. His sense of gratitude is expressed through practical acts of giving: "we provided them with colours, papers... we didn't take them back... like a sense of gratitude... we prepared it ourselves..." For Manoj, responsibility is not individualistic but collective: "Not

individually... if we work as a team towards a shared goal, I'm sure that we will be able to bring change in the society." Identity consolidation here is tied to teamwork and shared civic agency.

Across participants, identity consolidation emerges through two intertwined processes: affirmation from others and assumption of responsibility. Sharon gains confidence through student recognition. Amy reconstructs her self-understanding through relational exposure and expanded purpose. Manoj experiences belonging through welcome and team-based contribution. In each case, participants no longer position themselves merely as students completing a requirement, but as individuals who understand themselves as capable educators, contributors, and agents of meaningful change.

Theme 4: From Assumption to Empathy

Across participants, service-learning extended social awareness beyond the self and into relational space. What began as task-oriented engagement gradually became an encounter with difference, perspective, and mutuality. Through repeated exposure to students, teachers, parents, and community members, participants describe shifts in how they perceive others, approach interaction, and position themselves within social relationships. This expansion involved not only awareness of others' circumstances but also the development of adaptability, empathy, and collaborative confidence.

Sharon reflects on a movement away from self-centred action toward relational sensitivity: "I need to be considerate of people surrounding, people's environment and people's thinking, because I cannot go and impose my idea on them just for the sake of the completion of my own course... I must present my topic in a manner that they find it useful... not just one way... it also... benefits them..." Service-learning ensures not merely a course completion but ensuring mutual benefit.

Her awareness of adaptability deepens: "different kinds of person require a different kind of approach..." Social interaction becomes

adaptive rather than prescriptive. Recognition from students also anchors her socially: "ma'am, you are my favourite teacher... we still remember what you taught us... we miss you... please come and visit us..." She describes a broader shift in her social self: "I'm a very introverted, reserved person... it has brought a lot of changes, and I can see myself changing slowly..." Relational exposure thus reshapes her self-perception, social engagement becomes less threatening and more integral of identity.

Amy's account foregrounds empathy as a practice cultivated through relational exposure. She recounts handling a student caught cheating: "just because I saw it, doesn't mean that I will snatch it and... complain and shout at her... she might be going through something else..." Rather than reacting punitively, she pauses to consider unseen circumstances, replacing moral judgment with contextual understanding. She also reflects on navigating rejection during community outreach: "people can say no... it's okay for people to say no..." Interaction becomes a space of negotiation rather than expectation. Through engagement with teachers, students, and staff, she generalises this awareness: "everyone... going through their own... phase in life, and the important thing is to be kind to them..." Relational exposure produces humility: others are no longer obstacles or roles, but individuals navigating their own pressures, and kindness becomes the organising principle of her social engagement.

Manoj frames service-learning as a platform for learning from community members on their own terms: "it has helped me understand how people think... not with a preconceived notion..." The shift here is simultaneously cognitive and relational; preconceived assumption is suspended through repeated interaction. His description of being invited into a community home illustrates the dissolution of outsider status: "Come, come, come, have tea with us... not thinking, hey, these are outsiders... she prepared tea for us and snacks... It really seemed like, at home..." Hospitality

functions as relational inclusion: the boundary between service provider and community member softens. He also describes negotiating trust with parents: “parents were like... are you sure you guys will take... we will try our best...” Communication here involves reassurance, responsiveness, and accountability. He explicitly reflects on his growth: “It helped me with my communication skills... talking with the children... talking with the parents... I was also able to... have a sense of empathy towards the people, like, understanding their point of view...” Social growth thus involves skill development intertwined with attitudinal transformation.

Across participants, relational exposure destabilised self-enclosed perspectives and cultivated awareness of social complexity. Sharon learns not to impose her approach; Amy learns to interpret behaviour through empathy; Manoj learns to suspend preconceived notions and engage collaboratively. Communication becomes adaptive, empathy becomes practised rather than abstract, and collaboration emerges as a shared endeavour rather than unilateral intervention. Service-learning, in this sense, expands the social horizon not only by increasing interaction, but by reshaping how participants understand and inhabit relational space.

Theme 5: From Compliance to Genuine Commitment

Although all participants acknowledged the growth value of service-learning, their accounts reveal a consistent tension between institutional requirements and internally motivated engagement. Service-learning was experienced simultaneously as meaningful growth and as structured obligation. The grading system, hour-based completion requirements, and procedural compliance occasionally threatened to overshadow its deeper purpose.

Sharon describes navigating structural pressures alongside her personal growth: “I had to give importance to my academic parts also, but at the same time, I could not neglect Service-Learning also, so balancing, that was one challenge... we have that limited time hour

that we have to complete... Some schools outright rejected us... when we are working in a group five to six people, there will be five to six opinions... I have to listen to all and then choose whichever is the most appropriate...” The cumulative effect of these structural demands led her to acknowledge: “sometimes Service-Learning was very stressful... it was kind of a burden to me... I didn’t know how to go or navigate through it...” Yet she simultaneously recognised that growth emerged through this navigation: “as I started navigating through it... it has brought a lot of changes in me... I have grown personally a lot...” For Sharon, institutional structure initially felt restrictive, but meaning was recovered through persistence and adaptation.

Amy draws a sharper distinction between compliance and genuine commitment. She acknowledges early limited understanding but emphasises that service-learning must not be reduced to formality: “Service-Learning shouldn’t be a burden... rather than just doing it for formality, it’s better to not do it in the first place... if I am doing it just for formality... what is the point of Service-Learning...” She reframes it instead as: “an experience to be lived... to be cherished... to apply in our everyday life...” Contrasting its real-world relevance with theoretical coursework, she suggests that service-learning is something she would “take on to the real world.” For Amy, internally motivated service transcends institutional measurement; it becomes integrated into her sense of purpose.

Manoj offers the most explicit structural critique. While acknowledging the skill development that service-learning facilitated, he challenges the grading mechanism itself: “since it is a grade type system... students have to get this many numbers of hours... the grading... the hour system should be removed... they should not be bound...” He argues that coercion fundamentally undermines meaning: “if you force someone to do something like helping the people, then it is not of use...” His observation of peers requesting signatures and completing hours instrumentally, “can we do

four hours today?... can we give us the sign... can we just come and take picture and go?" illustrates how an institutional emphasis on hours can convert service into a mere requirement to undertake.

Across participants, the structural framework of service-learning was experienced as both enabling and limiting. It created opportunity while simultaneously enforcing compliance over relational commitment. Meaningful service, in their accounts, required internal motivation, genuine initiative, and engagement that extended beyond measurable hours. The tension between structure and internal motivation thus became central to how participants evaluated the experience: service-learning was transformative when freely chosen, but hollow when merely completed.

DISCUSSION

This study explored how university students at ADBU experienced and interpreted holistic development through service-learning. The findings indicate that holistic growth was not experienced as a direct or automatic result of participation. Rather, growth emerged through what students encountered and navigated during service-learning, particularly when they applied knowledge in real settings, confronted ethical discomfort, assumed responsibility, engaged relationally, and negotiated institutional demands. The first theme demonstrates the shift from the classroom knowledge to real-world meaning. This is consistent with experiential learning theory, within which learning deepens through cycles of concrete experience and reflective observation rather than remaining at the level of conceptual abstraction (Dewey, 1938; Kolb, 1984).

Participants described learning as becoming more "real" when they had to interact with people, adapt to context, and observe the effects of their engagement. This finding supports service-learning scholarship that emphasises the integration of academic content with community engagement as a mechanism for deepening understanding (Bringle & Hatcher, 1996; Eyler & Giles, 1999). Within the Assam

Don Bosco University (ADBU) framework, this pattern holds distinct practical implications: given that field placements encompass heterogeneous settings ranging from formal schools and Anganwadi centres to community-based organizations students frequently encounter applied challenges unanticipated by didactic instruction alone. Consequently, student involvement in the community emerges as the primary catalyst for the deepening of critical learning regarding social reality.

The second theme suggests the gradual movement from moral certainty to contextual judgement. Participants described situations in which they felt conflicted, uncomfortable, or genuinely unsure about what the right course of action was. Such moments of disorientation are frequently identified as central to transformative learning, where learners revisit earlier assumptions and develop more reflexive moral judgement (Mezirow, 1991, 2000). Participants' accounts also reflect moral reasoning becoming increasingly contextual, where values had to be negotiated within real structural constraints rather than applied as fixed principles (King & Mayhew, 2002). This dimension of moral growth is rarely captured through outcome-based instruments, reinforcing the value of phenomenological methodologies in illuminating how ethical formation actually unfolds (Mitchell, 2008). In the Indian higher-education context, where curricula are only beginning to formally integrate community-based ethics components under NEP 2020 (Ministry of Education, 2020), these findings suggest that moral development through service-learning is unlikely to occur through exposure alone: it appears contingent on programmes providing structured opportunities such as guided debriefing or reflection sessions for students to process disorienting ethical encounters rather than carry them unexamined.

The third theme highlights the enlargement of identity from student to contributor. Participants described increased confidence, courage, and a clearer sense of role, particularly

when trusted with meaningful tasks and when community members acknowledged their presence. This aligns with symbolic interactionist perspectives on identity, which propose that self-understanding develops through social interaction and the feedback of others (Blumer, 1969). Within service-learning scholarship, identity growth is similarly linked to the assumption of meaningful roles and the experience of oneself as capable of contributing (Bringle & Hatcher, 1995; Eyler & Giles, 1999). This finding has salience in the Indian undergraduate context, where professional identity formation is often deferred to the final years of study or to post-graduate training; participants' accounts suggest that sustained, responsibility-bearing community roles during undergraduate education may accelerate this process earlier than conventional curricular pathways typically allow.

The fourth theme reveals the journey from assumption to empathy. Participants described learning to communicate more adaptively, becoming less judgmental, and practising empathy in real interactions with diverse others. These experiences reflect the broader civic and interpersonal aims associated with service-learning (Bringle & Hatcher, 1996; Eyler & Giles, 1999). The findings also resonate with UNESCO's conception of education as "learning to live together," as participants described developing patience, relational understanding, and cooperative capacities through their sustained engagement (UNESCO, 1996). For ADBU and similarly situated institutions operating amid the linguistic and socio-economic diversity of North-East India, this suggests that the social value of service-learning lies not only in generic civic outcomes the primary indicators of success, there is a risk that the broader developmental aims of community engagement—including reflection, civic responsibility, and holistic growth—may receive less attention than the procedural requirements used to evidence participation.

Taken together, the five themes suggest that holistic development through service-learning is best understood not as a set of discrete

but in cultivating the cross-cultural communicative competence that NEP 2020 envisions as part of holistic education (Ministry of Education, 2020).

The fifth theme reveals a progression from compliance to genuine commitment. Participants valued service-learning but were critical of systems organised heavily around hours, grades, and procedural signatures. Their accounts suggest that when service-learning becomes primarily procedural, students are more likely to approach it as a requirement to be fulfilled rather than as an opportunity for meaningful engagement. This resonates with concerns in service-learning scholarship regarding the challenge of balancing institutional accountability with the preservation of authentic, reflective learning (Ash & Clayton, 2009; Furco, 1996). At the same time, Sharon's account suggests that students can still experience growth by learning to navigate structural pressures. The central issue, therefore, is not whether institutional structures exist, but whether they are designed to support student ownership and reflective engagement or to encourage performative completion.

This finding carries important implications for how Indian institutions operationalise UGC's (2022) recommendation for structured community engagement. Participants consistently described engagement in terms of fulfilling required hours, securing signatures, and meeting assessment expectations, indicating that institutional accountability mechanisms may shape how students understand and participate in service-learning. Where compliance-oriented measures become

outcomes but as an interpretative process in which applied challenge, moral disorientation, relational feedback, and institutional negotiation interact. The consistency with which participants distinguished between procedural completion and genuinely meaningful engagement across academic, moral, and structural domains alike indicates that this distinction is not incidental to their

experience but central to how they evaluate the developmental value of service-learning itself.

CONCLUSION

Holistic growth through service-learning emerged not as a discrete or predictable outcome but as a layered process shaped by applied engagement, ethical dilemma, relational learning, identity formation, and negotiation with institutional structures. Within Indian higher education, service-learning holds meaningful potential for supporting holistic educational aims as articulated in national policy frameworks (Ministry of Education, 2020; UGC, 2022); however, the depth of development depends on preserving the internal motivation that participants described while designing structures that genuinely encourage reflection and student ownership.

The findings suggest that institutions should not assume service-learning automatically produces holistic development; its developmental value appears to depend substantially on programme design and support. First, structured reflection, defined as facilitated sessions for interpreting ethical complexities and real-world constraints is critical for transforming raw field exposure into genuine developmental learning (Ash & Clayton, 2009). Second, institutions may need to reconsider overly mechanical assessment systems, such as strict hour-based compliance requirements, which participants associated with reduced sincerity and performative participation (Furco, 1996). Third, facilitation and supervision should actively support students in navigating moral ambiguity and real-world constraints, since these were central to their lived experience. In the Indian higher education context, where holistic education is a stated policy priority, these design choices matter considerably for aligning institutional aims with students' actual lived experience of service-learning (Ministry of Education, 2020; UGC, 2022). Future studies could include participants across multiple institutions, examine change over time through longitudinal designs, and incorporate the perspectives of faculty members and community partners to

enrich understanding of the relational and structural dimensions of holistic development through service-learning.

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CONFLICT OF INTEREST

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A study on the Challenges and Best Practices of Child Rights Clubs in Shillong

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ABSTRACT

Child Rights Clubs (ChRCs) function as participatory platforms aimed at enhancing awareness, leadership, and advocacy among children. In Shillong, ChRCs operate under the Child Friendly Shillong initiative to create child-friendly spaces and strengthen child participation. Despite their growing presence, limited empirical research has examined the challenges faced by members and the best practices adopted by ChRCs within the local context. This study aimed to identify the key challenges faced by members of ChRCs in Shillong and assess the best practices adopted by these clubs. A descriptive research design with a quantitative approach was employed in this study. Fifty members below the age of 18 years from three ChRCs in Shillong were purposively selected as respondents. Data were collected using a structured questionnaire consisting of closed-ended questions and were analysed using descriptive statistical techniques, including frequency and percentage analyses, with the aid of Microsoft Excel. The findings revealed that awareness campaigns were the most common activity conducted by the clubs (38%), followed by a combination of street plays, awareness drives, and leadership training (22%). Programmes on drug and substance abuse awareness were identified as the most successful initiative (40%). The study also identified several challenges affecting the functioning of the clubs, including delays in approvals and decision-making (22%), limited understanding of ChRCs among local authorities (18%), lack of resources and logistical support (14%), communication barriers, and inadequate guidance from facilitators. Overall, the study found that ChRCs in Shillong serve as important platforms for promoting child rights awareness and encouraging child participation. However, institutional coordination gaps, communication barriers, and limited mentoring support constrain their effective functioning. Strengthening stakeholder coordination, improving support systems, and expanding community outreach may enhance the sustainability and overall effectiveness of these clubs.

KEYWORDS: Child Rights Club, Child Participation, Empowerment, Challenges, Best Practices, Shillong

INTRODUCTION

Children are often described as the future of society, but they are equally important in the present as individuals who possess rights, dignity, and a voice of their own. Despite this recognition, many children across the world continue to face conditions that affect their safety, access to education, and overall well-being. According to the United Nations Convention on the Rights of the Child (CRC), a child is defined as any individual below the age of 18 and they are entitled to rights as well as special protection and care, regardless of gender, nationality, or social background (United

Nations [UN], 1989). On the 11th of December 1992, India signed the United Declaration on the CRC, which is one of the most critical steps in ensuring the protection and interest of a child (National Human Rights Commission [NHRC], 2019). Since its adoption, the Convention has significantly influenced India in formulating child-centred policies and strengthening constitutional and legal frameworks to safeguard and promote the rights of children. Key legislations such as the Right to Education Act (2009), the Juvenile Justice (Care and Protection of Children) Act (2015), and the Protection of Children from Sexual Offences Act

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(2012) aim to protect children from exploitation and to foster a safe, inclusive and supportive space where they can grow and develop with dignity (Bal Raksha Bharat, 2024).

However, experts on child rights are of the opinion that the scheme, law and policy to safeguard the rights of children are yet to be implemented effectively till date (NHRC, 2019). This gap in implementation is reflected in the number of reported child rights violations. According to the National Commission for Protection of Child Rights (NCPCR), reported cases of child rights violations increased from 2,404 in 2012–13 to 3,281 in 2013–14 and further to 3,340 in 2014–15. During 2015–16, a total of 2,270 cases had already been registered up to 30 June 2015 (Press Information Bureau, 2015). Thus, violence against children continues to be a widespread problem, affecting millions of children across all socio-economic sections of Indian society (UNICEF India, n.d.-a). In 2021, the Bosco Integrated Development Society (BIDS) launched the Child Friendly Shillong (CFS) initiative in Shillong, Meghalaya to implement protective strategies for vulnerable children and to improve community-oriented child protection frameworks through the promotion of child rights and available services (The Shillong Times, 2025).

As part of its efforts to promote and protect child rights, CFS has established 104 Child Rights Clubs (CRCs), benefiting more than 3,164 children, of whom over 2,300 are actively involved in the programme (BIDS, 2025). CRCs are child-friendly platforms that bring children together to learn about their rights and responsibility-ties, discuss issues that affect them and encourage active participation as agents of social change within their communities (The Shillong Times, 2025; Juma & Muoki, 2023). This initiative is in-tended to promote and protect children's rights by enhancing their access to the fundamental rights of survival, protection, development, and participation while providing them with a platform to voice their opinions, concerns, and advocate for children whose voices

are often unheard (Child Friendly Shillong et al., 2023; HP News Service, 2024). At the same time, existing literature highlights several challenges in ensuring meaningful child participation, emphasizing that children should be recognized as active citizens rather than passive recipients of adult decisions. In practice, however, participation is often constrained by adult as assumptions about children's age and maturity, resulting in power imbalances, tokenistic involvement, limited inclusion of marginalized and children with disabilities, and inadequate awareness of children's rights and opportunities for meaningful engagement (Muharman et al., 2026). These challenges are further compounded by limited public awareness of child rights, as a study conducted among 247 adults in Shillong found that 67% of the respondents were unaware of child rights (Child Friendly Shillong et al., 2023).

These findings suggest that when adults lack awareness of child rights, children are less likely to exercise and realize their rights effectively, as adults play a crucial role in creating supportive environments for meaningful participation and protection. Despite increasing attention to child participation at both national and international levels, there is still limited empirical research focusing on how CRCs operate in specific local contexts such as Shillong. Much of the existing literature provides a general overview of child participation but does not fully explore the practical challenges and best practices that emerge at the grassroots level.

This gap indicates the need for more context-specific studies to better understand how these clubs' function, the constraints they face, and the ways in which their effectiveness can be improved. Understanding both the strengths and the limitations of these clubs is therefore important. While they have significant potential to empower children and promote child-friendly environments, their long-term success depends on sustained support, active involvement, and collaboration among schools, families, NGOs, and the wider

community. In this context, the present study examines the challenges and best practices of CRCs in Shillong. By examining the functioning of CRCs, children's levels of participation, the challenges encountered, and the support systems that influence these clubs, the study seeks to generate context-specific evidence to strengthen child rights initiatives and contribute to a more inclusive, participatory, and protective environment for children in Meghalaya.

Objectives of the study

- i. To identify the key challenges faced by members of CRCs in Shillong.
- ii. To assess the best practices of CRCs in Shillong.

METHODOLOGY

The study followed a descriptive research design with a quantitative approach to examine the current challenges faced by members of CRCs and to assess the best practices adopted by these clubs in Shillong. A descriptive research design was considered appropriate because it facilitates the systematic description of the existing conditions and experiences of CRCs members. A multistage purposive sampling technique was employed in this study. In the first stage, CFS purposely selected CRCs based on their geographical location and active functioning. Due to time and resource constraints, only three clubs were included in the study, out of which, two were school-based and one was community-based.

The total population of the study consisted of 80 members across the three selected CRCs. In the second stage, 50 respondents below the age of 18 years were purposively selected based on their active participation and their willingness to participate in the study, with the assistance of the Child Rights Facilitators (CRF) of the selected clubs. Both boys and girls were included in the sample. Data were collected using a structured questionnaire consisting of closed-ended questions. The questionnaire focused on identifying the challenges experienced by club members and assessing the best practices adopted by the clubs.

The questionnaire was reviewed by content experts and language experts to ensure content validity, clarity, and appropriateness of language.

The collected data were analysed using descriptive statistics, including frequency distributions, percentages, and tabular presentations, to summarize and interpret the findings.

Ethical Considerations

Prior permission to conduct the study was obtained from the BIDS, under which the CFS project and the selected CRCs operate. Before data collection, the purpose and objectives of the study were clearly explained to all respondents. Informed assent was obtained from the child participants, and permission was sought from the respective schools and CRFs prior to data collection.

Respondents were informed of their right to refuse to answer any question and to withdraw from the study at any stage without any consequences. To ensure the quality and validity of the research instrument, the questionnaire was reviewed by content experts and language experts before its administration.

Throughout the study, confidentiality and anonymity of the respondents were strictly maintained. Personal information was not disclosed, and all data collected were used solely for academic and research purposes.

RESULTS

The findings of the study provide insights into the challenges faced by members of CRCs in Shillong and the best practices adopted by these clubs. The results are presented under three sections:

- A. Respondents' Profile, Motivation for Joining, and Awareness of Child Rights**
- B. Challenges Faced by Respondents as Members of the CRCs**
- C. Respondents' Perceptions of the Best Practices of CRCs**

These findings contribute to a better understanding of the experiences of CRCs members and the practices that support the promotion and protection of child rights.

A. Respondents' Profile, Motivation for Joining, and Awareness of Child Rights

Table 1: Reasons Respondents Joined the CRCs

Responses	n	%
Interest in Child Rights	31	62
For school/community involvement	11	22
Influence from peers/teachers	8	16
Total	50	100

The table shows that many respondents (62%) joined the CRCs due to their interest in child rights. This suggests that most members were motivated by a desire to learn about and promote the rights and well-being of children. In addition, 22% of the respondents joined the club to participate in school or community activities, while 16% were influenced by their peers or teachers. These findings indicate that personal interest, opportunities for community involvement, and encouragement from significant others played important roles in motivating respondents to become members of the CRCs.

Table 2: Respondents' Awareness of Child Rights

Responses	N	%
Yes	33	66
No	4	8
Not sure	13	26
Total	50	100

The table shows that many of the respondents (66%) reported being aware of child rights. This indicates that most members of the CRCs possess basic awareness of the rights and entitlements of children. However, 26% of the respondents stated that they were not sure about their awareness of child rights, while 8% reported that they were not aware of child rights. These findings suggest that although awareness of child rights is generally high among respondents, there remains a need for continued awareness and educational activities to strengthen understanding among all club members.

Table 3: Respondents' level of understanding of child rights

Responses	n	%
Right to go to school, safe and protected, play and rest, speak and be heard, good food, water and	35	70

healthcare, live with family and loved ones.		
The right to go to school	4	8
The right to be safe and protected	4	8
The right to speak and be heard	2	4
The right to live with a family that loves and cares for you	2	4
The right to play and rest	1	2
I am not sure/ I do not know	2	4
Total	50	100

The table shows that many of the respondents (70%) demonstrated a comprehensive understanding of child rights by identifying several key rights, including the right to education, protection, participation, health, family care, and recreation. This suggests that most CRCs members possess a broad understanding of the various rights entitled to children. A smaller number of respondents mentioned specific rights, such as the right to go to school (8%), the right to be safe and protected (8%), the right to speak and be heard (4%), the right to live with a caring family (4%), and the right to play and rest (2%). Only 4% of the respondents stated that they were not sure or did not know about child rights. Overall, the findings indicate a generally high level of understanding of child rights among respondents, although some members demonstrated knowledge of only particular aspects of these rights.

Table 4: Different Types of Child Rights Identified by Respondents

Responses	n	%
Right to development, protection, participation & Survival	37	74
Right to protection	5	10
Right to development	4	8
Right to survival	3	6
Right to participation	1	2
Total	50	100

The table indicates that a large majority of respondents (74%) were able to identify all four major categories of child rights, namely the right to survival, development, protection, and participation. This suggests a high level of awareness and understanding of the fundamental

rights of children among most CRCs members. A smaller number of respondents identified individual categories, including the right to protection (10%), the right to development (8%), the right to survival (6%), and the right to participation (2%). The findings indicate that most respondents were able to identify multiple categories of child rights, while some mentioned only specific categories.

A. Challenges Faced by Respondents as Members of the CRCs

Table 5: Challenges Encountered by Respondents While Working with the Local Government/Dorbar Shnong

Responses	n	%
Delay in approvals or decision-making	11	22
Limited understanding of CRCs	9	18
Lack of resources or logistical support	7	14
Communication barriers (language, formality, etc.)	3	6
Lack of interest or cooperation from local leaders	1	2
Not aware	19	38
Total	50	100

The table shows that 38% of the respondents were not aware of any challenges encountered while working with the Local Government or Dorbar Shnong. Among those who reported challenges, the most common was delay in approvals or decision-making (22%), followed by limited understanding of CRCs among local authorities (18%). Additionally, 14% of the respondents identified a lack of resources or logistical support as a challenge, while smaller proportions reported communication barriers (6%) and lack of interest or cooperation from local leaders (2%). These findings suggest that administrative delays, limited awareness of CRCs activities, and inadequate support from local institutions were the main challenges experienced by respondents in their engagement with the Local Government and Dorbar Shnong.

Table 6: Challenges Encountered by Respondents while working with other CRCs members

Responses	n	%
Lack of communication	10	20

Lack of cooperation or teamwork, Irregular attendance by members, Unequal participation in activities and Lack of communication	8	16
Lack of cooperation or teamwork, Differences in opinion or conflict and Lack of communication	6	12
Lack of cooperation or teamwork	5	10
Differences in opinion or conflict	5	10
Irregular attendance by members	5	10
Unequal participation in activities	2	4
Other	3	6
No challenges encountered	6	12
Total	50	100

The table shows that lack of communication was the most frequently reported challenge, identified by 20% of the respondents. Lack of cooperation or teamwork, differences in opinion or conflict, and irregular attendance by members were each reported by 10% of the respondents. Smaller proportions reported unequal participation in activities (4%) and other challenges (6%), while 12% stated that they had not encountered any challenges. Overall, the findings suggest that communication difficulties, limited teamwork, and inconsistent member participation were the primary challenges experienced by respondents when working with other CRCs members.

Table 7: Challenges Encountered by Respondents While Working with the CRFs

Responses	n	%
Lack of motivation or encouragement	11	22
Language or communication gap	9	18
Lack of regular follow-up or guidance	8	16
Infrequent meetings or communication	3	6
Infrequent meetings/ communication, language/ communication gap and lack of motivation or encouragement	1	2
Other	11	22
No challenges encountered	7	14
Total	50	100

The table shows the challenges respondents faced while working with the CRF. The findings reveal that 22% of the respondents reported a lack of motivation or encouragement, while another 22% of the respondents mentioned other challenges. A

language or communication gap was reported by 18% of the respondents and 16% of them stated that there was a lack of regular follow-up or guidance. Infrequent meetings or communication were reported by 6% of the respondents, while 2% of the respondents experienced a combination of infrequent meetings, language or communication gaps, and lack of motivation or encouragement. Additionally, 14% of the respondents stated that they did not face any challenges while working with the CRF. Overall, the findings suggest that communication barriers, inadequate guidance, and lack of motivation were the primary challenges encountered by respondents in their interaction with the CRF.

B. Respondents' Perceptions of the Best Practices of CRCs

Table 8: Types of Activities Conducted by the CRCs

Responses	n	%
Awareness Campaigns	19	38
Street plays, Awareness Campaigns and Leadership training	11	22
Peer discussions	7	14
Workshops, Awareness Campaigns and Peer discussions	6	12
Street Plays	5	10
Leadership training	1	2
Workshops	1	2
Total	50	100

The table shows the different activities conducted by the CRCs. The findings reveal that awareness campaigns were the most reported activity, mentioned by 38% of the respondents. A combination of street plays, awareness campaigns, and leadership training was reported by 22% of the respondents. Peer discussions were mentioned by 14% of the respondents, while street plays were reported by 10% of them. In addition, 12% of the respondents reported a combination of workshops, awareness campaigns, and peer discussions. Workshops alone and leadership training alone were each reported by 2% of them. Overall, the findings suggest that awareness campaigns are the primary activity of CRCs, often complemented by

interactive activities such as street plays, peer discussions, workshops, and leadership training to promote child rights awareness and participation among children.

Table 9: Initiated by Respondents through the CRCs

Responses	n	%
Awareness programmes related to children	11	22
Performed skits and dramas about good and bad touch and substance abuse.	9	18
Creative workshop activities	8	16
Sports, Dance, Awareness programmes & Cleaning drive	7	14
Acted in a drama about peer pressure and motivation	2	4
Tree plantation and cleaning drive	2	4
Focused on child rights understanding and safety	1	2
Made paintings and posters related to child rights	1	2
No initiative undertaken yet	9	18
Total	50	100

The table shows that awareness programmes related to children were the most initiated activities, reported by 22% of the respondents. This was followed by skits and dramas on good touch, bad touch, and substance abuse (18%), creative workshop activities (16%), and sports, dance, awareness programmes, and cleaning drives (14%). These findings indicate that respondents actively participated in awareness-raising, educational, and creative activities through the CRCs. A smaller proportion of respondents reported initiating activities such as dramas on peer pressure and motivation (4%), tree plantation and cleaning drives (4%), child rights and safety awareness activities (2%), and making paintings and posters related to child rights (2%). However, 18% of the respondents stated that no initiative had been undertaken by them through the club. Overall, the findings show that respondents participated in a variety of activities related to child rights, awareness creation, creativity, and community engagement, with awareness and advocacy-related

activities emerging as the primary initiatives undertaken through the CRCs.

Table 10: Respondents' Perceptions of the Most Successful Initiatives of the CRCs

Responses	n	%
Awareness program on Drugs and Substance abuse in schools and the community	20	40
Chart making on all types of Child Rights	9	18
Substance abuse and personal safety	6	12
Drama performance on good touch and bad touch	3	6
Group discussion on child safety	2	4
I do not know	10	20
Total	50	100

The table indicates that 40% of the respondents considered awareness programmes on drug and substance abuse conducted in schools and communities to be the most successful initiative of the CRCs. This was followed by chart-making activities on different types of child rights (18%) and programmes on substance abuse and personal safety (12%), highlighting the importance of awareness and educational activities within the clubs. A smaller proportion of respondents identified drama performances on good touch and bad touch (6%) and group discussions on child safety (4%) as the most successful initiatives. However, 20% of the respondents reported that they did not know of any successful project or initiative. Overall, the findings suggest that awareness-based programmes, particularly those addressing drug and substance abuse, are perceived as the most effective and successful activities undertaken by the CRCs.

Table 11: Activities Considered Most Impactful by Respondents

Responses	n	%
Awareness programmes on drug and substance abuse	12	24
Skits about good and bad touch	10	20
Writing their understanding of Child rights	8	16
Awareness activities for community involvement	7	14

Campaigns about drug and substance abuse	3	6
Sessions focused on helping students leave bad habits	2	4
I do not know	8	16
Total	50	100

The table shows that awareness programmes on drug and substance abuse were considered the most impactful activity by 24% of the respondents, followed by skits on good touch and bad touch (20%). This indicates that activities addressing child protection and substance abuse are perceived as highly beneficial by club members. Additionally, 16% of the respondents identified writing their understanding of child rights as the most impactful activity, while another 16% reported that they did not know which activity was most impactful. Awareness activities promoting community involvement (14%), campaigns on drug and substance abuse (6%), and sessions aimed at helping students leave bad habits (4%) were mentioned by smaller proportions of respondents. These findings suggest that awareness-based and educational activities are viewed as the most effective practices of CRCs.

Table 12: Respondents' Perceptions of who mostly supports the CRCs

Responses	n	%
Teachers/School	28	56
Parents or Guardians	8	16
Caring Community Group (CCG)	2	4
Child Rights Facilitators	2	4
NGO partners/ Local Community leaders	10	20
Total	50	100

The table shows that more than half of the respondents (56%) identified teachers and schools as the primary source of support for the CRCs. This indicates the significant role that schools and teachers play in facilitating club activities and encouraging member participation. Parents or guardians were reported by 16% of the respondents, while 20% of them identified NGO partners or local community leaders as the main supporters. In addition, 4% of the respondents each reported the

CCG and CRF as the primary source of support. These findings suggest that schools, along with community stakeholders, are perceived as the major contributors to the functioning and sustainability of CRCs.

Table 13: Messages Respondents Would Share About Being a Member of a CRCs

Responses	n	%
I would encourage others to join and be part of it.	19	38
I want to share the knowledge I gained, like good/bad touch	18	36
Younger students need to learn from it	3	6
CRCs helps children live rightfully and safely	2	4
It increases awareness about children's rights and safety	7	14
All the above	1	2
Total	50	100

The table shows the messages respondents share about being involved in the CRCs. The findings reveal that 38% of the respondents would encourage others to join and be part of the club. Another 36% of the respondents stated that they would like to share the knowledge they gained, such as information about good and bad touch. 6% said that younger students need to learn from the club, while 4% of the respondents reported that the CRCs helps children live safely and understand their rights. In addition, 14% of the respondents stated that the club increases awareness of children's rights and safety and 2% of them mentioned all the above messages. These findings demonstrate that respondents perceive CRCs as effective platforms for learning, awareness creation, and child empowerment.

Table 14: Respondents' Suggestions for Improving the CRCs

Responses	n	%
Organize awareness programs in the community	18	36
Conduct regular meetings and improve communication	12	24
Spread the CRCs club to other areas and schools	3	6
Invite more people to join the CRCs club	10	20
More games and activities	7	14

Total	50	100
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The table shows the respondents' suggestions for making the CRCs more effective. The findings reveal that 36% suggested organizing awareness programmes in the community, while 24% recommended conducting regular meetings and improving communication. 20% suggested inviting more people to join the club, 14% recommended including more games and activities, and 6% suggested expanding the CRCs to other areas and schools. These findings indicate that respondents believe greater community engagement, active participation, effective communication, and wider outreach are important for strengthening the functioning and impact of CRCs

DISCUSSION

The study explored the challenges experienced by members and the best practices adopted within CRCs in Shillong. In addition, background information on members' motivations for joining the clubs and their awareness of child rights was examined to provide context for the study. The findings are discussed in relation to existing literature on child participation and child rights initiatives in India. The results show that intrinsic motivation played a key role in children joining these clubs, with 62% reporting an interest in child rights and this aligns with motivation theory, which suggests that internal interest can support sustained engagement (Cherry, 2026).

The findings also revealed that 66% of the respondents were aware of child rights, while 74% correctly identified the four fundamental categories as child rights, namely the rights to survival, protection, development, and participation. These findings indicate that participation in Child Rights Clubs (CRCs) has played an important role in enhancing children's knowledge and understanding of their rights. In contrast, a study conducted among 247 adults in Shillong found that 67% of the respondents were unaware of child rights. The same study further reported that 88% lacked knowledge

of the right to survival, 83% were unaware of the right to protection, 79% did not know about the right to development, and 92% were unaware of the right to participation (Child Friendly Shillong et al., 2023). This contrast suggests that CRCs serve as effective platforms for educating children about their rights and fostering greater awareness than is evident among the wider adult population.

The finding shows that teachers and schools were perceived as the primary source of support (56%), followed by NGO partners and local community leaders (20%) and parents or guardians (16%), highlights the significant role of educational institutions and community stakeholders in fostering children's participation and ensuring the effective functioning of CRCs. This finding contrasts with existing literature, which suggests that children's participation is often constrained by adult attitudes that underestimate their abilities, leading to tokenistic participation and the exclusion of marginalized children (Muharman et al., 2026).

The findings of the present study indicate that when teachers, schools, families, and community stakeholders provide active support, they can create an enabling environment that encourages meaningful child participation and strengthens the functioning of CRCs. Besides these positive aspects, the study also identified several challenges at both the institutional and interpersonal levels. At the institutional level, respondents reported delays in approvals from the Dorbar Shnong/local government (22%), limited understanding of the clubs among local authorities (18%), and inadequate support (14%). Among club members, poor communication (20%), lack of cooperation (10%), and irregular attendance (10%) emerged as key challenges. Regarding Child Rights Facilitators (CRFs), 22% of the respondents reported a lack of motivation and encouragement, while another 22% identified other unspecified challenges. These findings underscore the importance of well-trained and committed facilitators in ensuring the effective

functioning of Child Rights Clubs. As noted by Alka D (2024), sensitisation workshops were conducted with government and non-governmental organisations to identify suitable facilitators, who subsequently received structured training on child rights, relevant laws, local governance, and their roles and responsibilities, enabling them to effectively engage with, encourage, and inspire children to participate actively. Respondents identified programmes addressing drug and substance abuse (40%) as the most successful initiatives undertaken through the CRCs. Respondents further reported that they had taken the initiative to organize awareness programmes (22%), stage skits on good touch and bad touch (18%), and implement various other child rights-related activities. The prominence of these initiatives reflects the relevance of CRC activities in responding to issues affecting children in the local context. Recent reports indicate that children in Meghalaya are being exposed to drug use at an alarmingly young age, with initiation reported as early as 10 years, substantially younger than the average age (22 years) reported in neighbouring states such as Manipur and Nagaland (CNBC-TV18, 2025; Press Trust of India, 2025).

Evidence from the National Family Health Survey (2019–21) underscores the continuing vulnerability of children to sexual violence, reporting that 1.5% of women aged 18–29 experienced such violence before the age of 18 (UNICEF India, n.d.-b). These findings suggest that the awareness and preventive activities conducted through CRCs are timely and play an important role in equipping children with knowledge and skills to recognize risks, protect themselves, and make informed decisions.

The positive perceptions of CRCs among the respondents were further reflected in their willingness to encourage others to join the clubs (38%) and to share the knowledge and awareness they had gained through their participation (36%). Overall, the findings demonstrate that CRCs in

Shillong play a significant role in enhancing children's awareness of their rights, encouraging meaningful participation, and equipping them to address issues affecting their lives through awareness programmes and other child-led initiatives.

CONCLUSION

This study analyses the function of CRCs in Shillong, focusing on the challenges that the respondents face and the best practices of the club. The findings show the importance of social support networks such as teachers/schools, NGOs, facilitators and community caring groups in fostering an environment that promotes children's participation. Constraints such as institutional delays, limited support from Dorbar Shnong (local governance institutions), communication gaps, and lack of motivation from facilitators are hurdles to effective function of the CRCs. Review shows that strengthening collaboration with Dorbar Shnong, continuous capacity-building and mentoring of Child Rights Facilitators, and greater involvement of families and the wider community could enhance the sustainability and effectiveness of CRCs in promoting and protecting children's rights. The study also shows that CRCs are child friendly platforms that enhance children's awareness of their rights, promote meaningful participation and equip them to address issues affecting their lives. As respondents reported active involvement in awareness programmes, street plays, peer discussions, and campaigns on issues such as substance abuse prevention, child safety, and child rights. To conclude, CRCs is a potential platform that promotes child rights and encourages meaningful child participation in Shillong, thereby making a significant contribution to building child rights-friendly communities in Meghalaya.

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CONFLICTS OF INTEREST:

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Wage Differentials in Northeast India with Special Reference to the Service Sector

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ABSTRACT

This paper explores disparities in wages across sectors in Northeast India during the post-liberalization period from 1993-94 to 2019-20, with special emphasis on the service sector based on the NSSO data. The results point to the uneven wage growth in the region, characterized by sectoral, gender, educational, and occupational wage segmentation. Urban workers and the ones working in secondary and service sectors earn more than those in primary sector. Even within the service sector, disparities are evident. Services such as banking, insurance, public administration & defends, education, and healthcare pay relatively higher wages, whereas trade, hotels, restaurants, and personal services remain low-paying services. A consistent gender wage gap is observed across all sectors, education levels, and occupations, including among highly educated professionals. The findings also indicate that wages increase with higher educational attainment, although it varies across occupations, with legislators, senior officials, managers, professionals, and technicians earning the highest wages. Inter-state differences further reflect uneven regional development, with states like Mizoram, Sikkim showing comparatively higher wages. To enhance inclusive and balanced wage growth in the region, the study points to the importance of promoting quality employment, reducing occupational and gender-based inequalities, addressing rural-urban and inter-state disparities.

KEYWORDS: Wage disparities, Northeast India, Service sector employment, Labour market segmentation, post-liberalization period.

INTRODUCTION

Gender wage inequality remains a persistent feature across countries, sectors, and occupations, affected by differences in education and skills, labour market structures, occupational segregation, and societal norms (Hisarcıklılar & Ercan, 2005; ILO, 2019). Although improvements in education and skill development have helped reduce the gap in gender wage, women are found facing significant discrimination, especially in informal and low-paying jobs (Das, 2012; Lee & Wie, 2015). According to the ILO (2019), globally, women's average earnings remain below those of men with disparity varying widely, reaching as high as 45 % in some

countries, while in others it is minimal or absent. Wage differences between female and male have long existed in labour markets. For instance, Hisarcıklılar & Ercan (2005) found that in Turkey, women's improved education and skills helped reduce the wage gap, but discrimination persisted. Similarly, Terada-Hagiwara, Camingue-Romance & Zveglic (2018) asserted that a higher concentration of women in industrial sectors could widen the wage gap, especially in developing countries, where women with greater number of children faced even greater disadvantages. In China and India, changes in urban labour markets during the 1990s and 2000s showed mixed outcomes: while increasing women's educational

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attainment helped reduce. Rising female education levels helped narrowing the gender wage differentials in India, whereas in China the gap increased (Lee & Wie, 2015). Wage inequality has broader implications, as it contributes to disparities in income, consumption, health, and education, particularly in developing countries, hence, reducing wage disparities remains an important policy concern in countries like India (Mukherjee & Majumder, 2011). A substantial share of wage differential can be attributed to human capital determinants including education, experience, occupation, and location (Deming, 2022). However, inequalities also stem from disparities between formal and informal sectors, place of residence- rural-urban, and types of employment type where informal sector workers typically earn lower wages, face poor working conditions, and lack social security, while those in formal or semi-public sectors enjoy better pay and greater job security (Das, 2012). Das (2012), in analysing the major determinants of wage inequality as considered in the human capital theory which includes of education, experience and disparities in job availability, type and sector of employment and earnings, and other personal or household characteristics, opined that male-female differential is partly due to men having better access to high-paying jobs, while women- especially those with limited education-often struggle to secure quality employment. Even when women enter similar occupations, they are frequently paid less, reflecting both occupational segregation and discrimination. Mukherjee & Majumder (2011) further emphasise that these disparities are associated with women's limited bargaining power in the labour market. Determinants of wages significantly contribute to patterns of wage inequality. Therefore, gender wage disparities can be interpreted through multiple perspectives: neoclassical theories emphasise differences in human capital, labour market segmentation theories point to structural barriers, and feminist approaches highlight the role of patriarchy and social norms in

maintaining inequality (Hisarcıklılar & Ercan, 2005). Against this backdrop, the paper aims to examine average daily wage differentials in Northeast India focusing on the service sector during 1993-94 to 2019-20. The issue carries important economic significance, given that wage differentials form the crucial determinants of disparities in living standards. This paper explores issues of wage rates or earnings in the labour market over the last decade across sector, gender, and job types, industry and occupational categories. Hence, firstly, the paper looks at the gender wage differentials in the economy by broad sector- primary, secondary and service sector; rural-urban residence between two time points, i.e., 1993-94 and 2019-20. Secondly, the wage differentials are also analysed in the service sector by sex, rural-urban, educational level and occupational groupings in Northeast India. The paper proceeds as follows. Section 2 outlines data source and methodology used in the study. Section 3 provides the findings, whereby wage differentials for the broad sectors by rural-urban residence and sex are presented in section 3.1 and 3.2, while the wage differentials of service sector are discussed in section 3.3. Section 4 presents conclusions and implications of the paper.

METHODOLOGY

Micro unit datasets of Employment and Unemployment Surveys (EU) and the Periodic Labour Force Survey (PLFS) from the National Sample Survey Office (NSSO), Government of India, constitute the data source, viz., Survey of EU in the 50th round (July 1993 to June 1994) and PLFS (July 2019 to June 2020). Data used in the paper are workers, or employment, wages, industry, educational levels, occupational groups. The study follows the National Accounts Statistics classification of India, grouping economic activity into primary, secondary, and service sectors. Primary sector consists of agriculture & allied activities consisting of cultivation, forestry, fishing, mining & quarrying; secondary sector consists of manufacturing, construction, utilities such as electricity, gas & power supply; and the

remaining activities constitute the service sector (CSO, 2012). Service sector can be further categorised into trade, hotel & restaurant; transport, storage & communications; financial services, banking and services; real estate, renting & business services; public administration & defence; education, health & social work; and other personal and community services (CSO, 2012). Although official classifications have been revised over the years, data comparability is unaffected since reclassified activities remain within these broad sectoral groupings. In the NSS surveys, individuals are classified as employed if they are engaged in any economic activity or are temporarily away from work while maintaining a connection to such activity due to reasons such as illness, injury, physical disability etc., requiring short-term absence (NSSO, 2013). Individuals are assigned into various activity categories depending on the activities they pursued during specified reference periods, namely, one year (usual status), one week (current weekly status), and each day of the reference week (current daily status). In this study, employment or worker estimates use the usual principal activity status (UPS) using major time criterion, which identifies individuals who were employed for most of the year preceding the survey. Industry-specific employment statistics are calculated using the National Industrial Classification (NIC) at 2-digit level, with NIC-1987 applied for the 1993-94 survey and NIC-2008 for the 2019-20 survey. Additionally, occupational classification is carried out using the National Classification of Occupations (NCO) at 2-digit level. Following the classification of NSSO, occupations are grouped into the following categories : (i) legislators, senior officials, managers, professionals, and technicians; (ii) clerks, service workers, and sales personnel; (iii) skilled agricultural and fishery workers; (iv) craftsmen and plant and machine operators; and (v) elementary occupation workers and labourers. For this purpose, NCO-1968 is used for 1993-94 and NCO-2004 for 2019-20. As we know Consumer Price Index (CPI) numbers

are commonly used to adjust wages and salaries, calculate real wages, revise prices in business and individual contracts, deflate income and value series in national accounts, and conduct price analysis (Labour Bureau, 1989). The paper uses this CPI to deflate workers' current wages to constant 2011-12 prices. According to the Indian statistical system, earnings is defined as the wage or salary income received or receivable by wage or salaried employees and casual labourers for work performed during the reference week (NSSO, 2012). This study uses the CPI for Agricultural Labourers (CPI-AL) deflator for the rural sector and CPI for Industrial Workers (CPI-IW) deflator for the urban sector, to construct the CPI. CPI indexes are constructed using the retail prices of the total commodities or the General Index in all cases (CSO, 2012). For calculating CPI index, the items of these goods and services are categorized into six broad groups: a) food, b) Pan, supari, tobacco and intoxicants, c) Fuel and light, d) Housing, f) Clothing, Bedding and Footwear and g) Miscellaneous. The weighting diagram and the retail prices are the two essential constituents of CPI series. The weighting diagram is constructed at the start of the series, usually using a family budget survey conducted to measure the consumption behaviour of the CPI reference population. Combined with the base prices of goods and services, this weighting diagram forms the basic framework on which the index series is periodically constructed. Multiple CPI series have been introduced in India over time to support wage regulation and economic policy in a developing economy (CSO, 2010). For comparison across different periods, CPI series based on different reference years are linked using Simple Arithmetical Ratio Method. This method uses a linking factor derived from the old series for the base period of the new series, allowing the new index values to be converted into comparable estimates of the earlier series. Monthly prices data are collected from 600 villages across 20 states. CPIAL data for 1993-94 are available at the 1960-61 base, while later data are reported

at the 1986-87 base. The revised series (1986-87 = 100), introduced in November 1995, is compiled using NSSO price data following the methodology of the Technical Advisory Committee on Price Statistics. The old series weights were based on the 1956-57 Agricultural Labour Enquiry, while the new series weights use expenditure data from the 38th NSS round (1983). State-specific linking factors are applied to convert the new series to the old base. However, the conversion factor for Assam is as follows:

Index of Assam on old base = $5.89 \{ (0.8126 * \text{Index of Assam on new base}) + (0.0491 * \text{Index of Manipur on new base}) + (0.0645 * \text{Index of Meghalaya on new base}) + (0.0692 * \text{Index of Tripura on new base}) \}$

And the conversion factor for Punjab is:

Index of Punjab on old base = $6.36 \{ (0.6123 * \text{Index of Punjab on new base}) + (0.3677 * \text{Index of Haryana on new base}) + (0.0200 * \text{Index of Himachal Pradesh}) \}$.

CPIIW has three base series, viz., 1960, 1982, and 2001. This study uses the 1982 and 2001 series since data from the study period (1993-94 onward) are available only on the 1982 base. The 1982=100 series replaced the 1960 base in October 1988, expanding coverage to 7: factories, mines, plantations, railways, public motor transport, electricity, and ports and docks; and 55 increasing centres from 50 to 70. Weights were derived from the 1981-82 Working Class Family Income and Expenditure Survey, defining a working-class family as one earning at least half its income from manual work in these sectors. State-level urban deflators are constructed using weighted centre averages, with linking factors available only for common centres. The CPIIW 2001=100 series, released in March 2006, replaced the 1982 series and covers 78 industrial centres selected by industrial importance and employment from up to five centres per state in each sector. Indices are compiled at sub-group, group, and general levels using weights from the 1999–2000 Working-Class Family Survey. Given the unavailability of CPI-AL for some states and Union Territories, indices from neighbouring

states are used (e.g., Assam for northeastern states, Tamil Nadu for Pondicherry and Andaman & Nicobar Islands, Maharashtra for Goa and Dadra & Nagar Haveli). Delhi's CPIIW is used across rural and urban regions, with similar substitutions applied elsewhere. For analysis conducted at the national level (all-India), all Indian states and union territories are grouped into 35 units, and estimates are computed by considering them together. For estimating the North Eastern Region (NER) level, the study grouped the eight states of the region together.

RESULTS AND DISCUSSIONS

Wage differentials by broad sectors: The comparative overview of average daily wages in the primary, secondary, and service sectors, disaggregated into rural and urban regions of Northeast India relative to the national average for 1993-94 and 2019-20 at 2011-12 constant prices is shown in table 1. The findings reveal a significant rise in real wages over the study period across all sectors and states in the region. However, notable differences in wages remain across sectors, places of residence, and states. A clear sectoral pattern is visible, with the tertiary sector consistently offering the highest wages while the primary sector remains the lowest paid, despite accounting for substantial workforce. This indicates the slow structural transformation in the labour market. Similar patterns have been documented by Ghani & Kharas (2010, p.16) who note that service sector wage growth in India is higher than that of the manufacturing and agriculture. This also reflects the dual nature of the Indian economy, where rural areas tend to be subsistence-oriented while urban areas largely driven by market-based systems and capitalist tendencies (Reddy, 2015). Over time, the wage differential between primary and service sector wages has widened, indicating higher returns to non-agricultural employment. A strong rural-urban wage gap is observed in both periods. Urban workers are found consistently earning much more than rural workers with the biggest gap in the service sector, where better-paying jobs are substantially concentrated in the urban. Despite

rural wages increasing over time, their growth has been slower than in urban areas. In fact, Dutta (2005) noted that unequal wage distribution in India rose significantly during the 1990s. There are also clear inter-state differences within the region. States like Sikkim, Mizoram, and Nagaland report relatively higher wages, while Assam and Tripura lag, particularly in the primary sector. Compared to all-India levels, the region continues to fall behind in most sectors, especially in agriculture, though the gap is smaller in the service sector. Overall, the findings point to rising wages alongside continuing structural inequalities in the region. The dominance of low-paid primary sector employment in rural and the concentration of higher wages in urban secondary and service sectors indicate an incomplete process of structural transformation in Northeast India.

Wage Differentials by Sex: Table 2 highlights the clear differences in daily earnings between men and women across major sectors for both 1993-94 and 2019-20. In general, male workers receive higher wages than female workers, although the disparity is relatively lower in Nagaland and Sikkim. Over time, real wages have risen both in the region and across the country, indicating an overall improvement in earnings. However, the pace of this growth varies across sectors and gender. The wage disparity between primary and tertiary sectors has widened by 2019-20, suggesting that jobs in industry and especially in services are becoming more rewarding. Despite an increase in women's real wages there remains room for alignment between men's wage. In a certain case, particularly in the tertiary sector in Nagaland and Sikkim in 1993-94, women's wages were comparable to or slightly higher than men's, but they were limited and lacked long-term continuity. Findings further indicate that rising wages have not eliminated inequality. Male and female workers remain distributed across different job categories and occupations, which further widens the gender wage disparity. This suggests the importance of

improving female worker's access to better-paying jobs, particularly in the secondary and tertiary sectors, and addressing ongoing gender disparities in the labour market.

Wage differentials in the Service Sector: Pronounced intra-sectoral and gender-based wage differentials are also visible when examining the average daily wages of service sector workers, as outlined in the subsequent tables from table 3 through 6 and figure 1. Table 3 and 4 present the gender and sectoral wage differentials across the different sub-sectors of service sector are shown. They show that wage differentials also occur due to variation of salary across service industries. Financial services, banking & insurance (FBI), real estate, renting & business activities (RRB), education, health & social work (EHS), are observed as high-wage service activities. In contrast, trade, hotels & restaurants (THR), which employ a large share of workers, and other services such as personal and community services are relatively low paying. These indicate profound segmentation within the service sector. These earnings differences are commonly linked to variations in sectoral productivity, with higher wages associated with more productive activities (Aggarwal & Kumar, 2015). Surprisingly, except for Assam and Tripura, wages of services workers in the region are found higher than all-India level. Therefore, gender disparities are observed, with male workers generally earning more than female workers across most service activities. Exceptions are found in transport, storage & communication (TSC), and FBI in some states of the region and at the all-India level in recent years, as reported in Table 4.

Among service activities, FBI followed by EHS record the largest gender wage gaps. For males, wages are particularly high in FBI and EHS in states such as Sikkim, Mizoram, and Assam, while public administration and defence (PAD) also offers relatively stable and high remuneration across the region. Female workers, although concentrated in fewer subsectors, record comparatively higher wages in PAD and EHS, especially in Mizoram,

Nagaland, and Sikkim. Nevertheless, female wages remain lower than male wages in the

corresponding subsectors, reflecting persistent gender wage gaps within services.

Table 1: Average daily wage of workers by UPS by broad sector and rural-urban residence in 1993-94 and 2019-20 at 2011-12 constant prices in Northeast India

Rural					Urban				Total			
State/ sector	P	S	T	Total	1993-94							
					P	S	T	Total	P	S	T	Total
AP	84.09	102.54	181.99	133.99	263.15	161.74	222.33	205.23	97.88	125.98	197.74	156.94
ASS	85.22	116.1	222.98	110.97	385.92	203.26	226.34	244.97	91.88	142.03	224.22	127.04
MANI	145.26	120.33	223.53	182.21	122.35	212.52	263.31	233.97	140.59	149.04	242.01	201.17
MEGA	92.8	137	238.13	137.31	111.96	126.57	261.64	246.89	92.88	134.05	250.55	165.74
MIZO	105.8	193.56	312.44	172.18	114.79	187.8	298.55	249.85	107.61	189.69	303.32	207.54
NAGA	270.53	164.82	254.33	249.23	123.65	186.03	267.37	256.81	251.11	177.52	260.39	252.76
SIKK	106.33	155.65	264.19	197.18	NA	130.65	274.31	258.26	106.33	153.88	265.55	202.38
TRIP	103.81	105.56	185.67	134.28	139.74	95.4	245.99	232.5	104.32	104.14	206.67	151.99
NER	88.41	119.22	221.9	120.48	299.92	183.89	241.4	242.12	94.39	138.19	229.54	139.75
All India	66.98	114.66	195.6	90.41	140.12	220.59	279.75	245.23	70.55	169.76	247.85	134.61
2019-20												
AP	213.83	433.91	502.34	329	412.58	551.22	556.82	544.79	219.7	474.32	520.69	369.44
ASS	190.33	213.8	301.69	238.01	480.23	298.57	383.55	370.7	197.01	225.86	319.12	255.06
MANI	222.01	218.56	364.53	279.19	237.53	214.17	351.47	306.66	223.42	217.01	359.14	287.49
MEGA	163.2	206.96	270.19	198.75	261.86	273.6	445.83	412.91	163.74	218.57	338.61	235.43
MIZO	228.65	264.21	475.73	312.32	259.6	302.22	498.86	435.19	233.66	284.59	490.94	369.6
NAGA	198.00	249.61	402.58	288.6	151.64	295.79	485.62	441.27	194.48	260.42	442.71	336.77
SIKK	148.57	290.63	335.8	254.19	748.27	317.42	474.96	440.91	153.22	298.39	388.98	301.58
TRIP	176.79	191.6	245.5	200.84	147.67	216.14	330.8	291.08	175.75	196.68	276.94	219.05
NER	189.47	215.97	311.04	239.63	349.75	281.33	402.1	372.73	194.47	227.78	336.68	262.01
All India	171.87	208.35	254.4	198.56	268.54	306.69	386.74	355.14	175.88	248.09	329.17	248.4

Note: P= primary sector, S- secondary sector, T=tertiary/service sector

AP= Arunachal Pradesh, ASS=Assam, MANI=Manipur, MEGA=Meghalaya, MIZO=Mizoram, NAGA=Nagaland, SIKK=Sikkim, TRIP=Tripura, NER- Northeastern Region of India

Source: Authors' calculation from NSS Surveys on EU in the 50th round (1993- 94) and PLFS in 2019-20

Table 2: Average daily wage of worker by UPS by broad sector and sex in 1993-94 and 2019-20 at 2011-12 constant prices in Northeast India

Sector	Primary			Secondary			Tertiary		
1993-94									
State /Sex	Male	Female	Total	Male	Female	Total	Male	Female	Total
AP	112.95	67.45	97.88	134.58	57.86	125.98	201.83	156.83	197.74
ASS	96.45	77.46	91.88	142.34	138.6	142.03	232.86	177.27	224.22
MANI	144.13	128.75	140.59	185.08	77.89	149.04	249.08	205.92	242.01
MEGA	96.36	86.76	92.88	140.29	105.6	134.05	254.43	236.84	250.55
MIZO	112.91	84.37	107.61	191.46	171.9	189.69	304.92	296.55	303.38
NAGA	251.11	NA	251.11	178.16	164.86	177.52	259.39	266.04	260.39
SIKK	110.54	82.98	106.33	167.18	88.8	153.88	264.32	271.16	265.55
TRIP	117.22	52.02	104.32	110.62	61.07	104.14	219.1	145.58	206.67
NER	99.61	78.01	94.39	142.94	103.69	138.19	236.94	191.2	229.54
All India	80.27	51.55	70.55	188.01	77.88	169.78	257.84	199.58	247.85
2019-20									
AP	233.13	157.03	219.7	482.71	396.88	474.32	554.96	382.58	520.69
ASS	215.68	104.99	197.01	233.43	142.04	225.86	327.32	276.38	319.12
MANI	232.29	175.36	223.42	265.07	131.36	217.01	381.39	312.03	359.14
MEGA	184.07	106.76	163.74	226.69	163.86	218.57	380.49	259.49	338.61
MIZO	256.32	168.54	232.97	293.69	234.47	284.59	533.27	390.22	490.94
NAGA	211.33	112.31	194.48	272	152.81	260.42	430.23	480.21	442.71
SIKK	175.81	93.16	153.22	313.27	232.63	298.39	393.33	381.51	388.98
TRIP	190.23	116.23	175.75	218.07	103.25	196.68	304.09	178.02	276.94
NER	212.55	113.43	194.45	239.58	141.97	227.78	347.69	292.99	336.68
All India	194.05	114.05	175.9	269.52	132.45	248.1	340.89	281.55	329.11

Note: P= primary sector, S- secondary sector, T=tertiary/service sector

AP= Arunachal Pradesh, ASS=Assam, MANI=Manipur, MEGA=Meghalaya, MIZO=Mizoram, NAGA=Nagaland, SIKK=Sikkim, TRIP=Tripura, NER- Northeastern Region of India

Source: Authors' calculation from NSS Surveys on EU in the 50th round (1993- 94) and PLFS in 2019-20

Table 3: Average daily wages of worker in the service sector in 1993-94 at 2011-12 constant prices in Northeast India by sex

Sex	Male							
State/ sector	THR	TSC	FBI	ROB	PAD	EHS	OTH	Total SS
AP	160.89	136.04	82.86	187.53	211.81	289.15	127.18	200.03
ASS	133.93	193.75	331.28	282.12	246.19	292.11	115.8	218.51
MANI	311.01	142.05	NA	417.32	250.43	314.94	151.15	247.11
MEGA	165.1	191.81	288.07	NA	269.51	308.04	95.36	243.94
MIZO	265.86	254.25	0.82	412.16	291.02	373.82	270.25	307.17
NAGA	112.02	184.58	260.01	NA	275.39	274.7	140.37	259.39
SIKK	94.98	147.27	475.92	N A	273.57	412.19	105.9	263.27
TRIP	101.42	142.21	373.68	111.57	259.23	258.39	90.31	162.87
NER	145.7	181.29	328.18	267.88	254.03	293.44	107.4	215.99
All India	138.31	220.24	504.25	239.56	325.92	346.12	111.34	255.33
Sex	Female							
State/ sector	THR	TSC	FBI	ROB	PAD	EHS	OTH	Total SS
AP	NA	77.05	309.12	NA	125.59	267.07	64.34	156.83
ASS	84.26	163.87	239.72	185.47	223.04	249.9	65.5	163.93
MANI	73.11	89.89	NA	159.08	271.44	206	95.98	200.12
MEGA	209.08	244.05	NA	123.65	267.43	217.02	69	210.36
MIZO	202.68	NA	NA	NA	368.87	332.04	256.4	303.21
NAGA	299.65	N A	N A	N A	268.59	269.82	224.09	266.04
SIKK	NA	N A	N A	N A	268.82	354.27	23.38	271.16
TRIP	59.93	52.98	412.57	30.68	195.67	202.4	58.54	112.28
NER	112.88	148.14	257.93	161.17	242.04	244.88	66.99	171.2
All India	101.89	289.32	485.38	218.98	289.63	255.51	61.01	197.93

Note: TSC= transport, storage & communication, THR=trade, hotel & restaurant, FBI= financial services, banking & insurance, RRB= real estate, renting, business service, PAD= public administration & defence, EHS= education, health, social work, OTH= other services community, personal & social activities etc., Total SS: Service sector

Source: Authors' calculation from NSS Surveys on EU in the 50th round (1993- 94)

Table 4: Average daily wages of worker in the service sector in 2019-20 at 2011-12 constant prices in Northeast India by sex

Sex		Male						
State/ sub- sector	THR	TSC	FBI	ROB	PAD	EHS	OTHR	Total
AP	362.29	425.01	676.88	506.96	772.56	760.32	352.25	554.96
ASS	267.93	247.23	555.29	467.83	568.23	593.32	239.76	327.32
MANI	294.04	238.32	375.64	484.35	523.62	471.95	235.17	381.39
MEGA	274.05	226.69	593.56	352.54	643.85	501.58	258.57	380.49
MIZO	407.09	351.69	688.27	613.31	656.77	682.91	435.57	533.27
NAGA	350.25	260.06	1179.5	567.98	569.26	549.47	288.85	430.23
SIKK	325.39	236.56	561.8	595.21	426.55	759.65	226.08	393.33
TRIP	244.32	205.96	303.5	392.46	578.51	501.45	285.24	304.09
NER	273.94	246.83	532.36	478.61	583.67	579.03	249.2	347.69
All India	279.26	318.83	524.83	414.98	536.29	517.39	205.73	340.89
Sex		Female						
State/ sub- sector	THR	TSC	FBI	ROB	PAD	EHS	OTHR	Total
AP	277.6	438.95	715.07	414.92	614.49	391.28	203.12	382.58
ASS	167.18	306.71	277.17	390.77	307.18	329.09	170.48	276.38
MANI	197.61	209.95	175.15	343.5	391.92	394.17	207.45	312.03
MEGA	97.86	157.06	NA	379.45	670.68	261.27	237.64	259.49
MIZO	260.29	374.98	701.73	591.92	501.51	513.86	226.51	390.22
NAGA	287.25	312.55	NA	437.39	397.46	619.79	195.49	480.21
SIKK	204.26	193.22	558.65	199.01	383.01	462.14	211.6	381.51
TRIP	114.39	45.34	129.5	354.57	414.95	181.29	58.77	178.02
NER	180.34	262.23	306.79	411.65	451.85	340.24	173.45	292.99
All India	151.12	391.13	533.37	388.27	360.73	329.15	135.96	281.55

Note: TSC= transport, storage & communication, THR=trade, hotel & restaurant, FBI= financial services, banking & insurance, RRB= real estate, renting, business service, PAD= public administration & defence, EHS= education, health, social work, OTH= other services community, personal & social activities etc.,
Total SS: Service sector

Source: Authors' calculation from NSS PLFS in 2019-20

Table 5: Average daily wages of worker in the service sector in 2019-20 at 2011-12 constant prices by sex and educational levels in Northeast India

Sex	Male								
State/ Edu	1	2	3	4	5	6	7	8	Total
AP	343.71	409.58	463.88	389.42	404.79	487.98	654.7	838.99	566.98
ASS	183.67	308.14	219.82	218.15	245.57	333.73	439.04	590.69	335.61
MANI	262.84	121.89	179.6	223.44	265.42	351.93	400.78	483.78	390.57
MEGA	245.51	201.29	216.53	222.51	314.33	351.74	514.88	540.37	383.74
MIZO	550.03	NA	236.82	223.7	386.86	462.24	546.09	647.15	535
NAGA	388.9	NA	360.82	258.23	323.09	384.06	387.05	658.12	448.42
SIKK	203.68	248.95	237	333.22	338.59	364.63	415.44	629.95	397.64
TRIP	204.87	152.75	173.85	243.87	258.29	325.62	339.77	452.22	305.58
NER	198.11	245.91	225.42	225.5	260.86	345.15	443.67	578.18	356.08
All India	206.37	233.16	217.4	234.32	241.75	299.54	349.57	566.06	352.03
Sex	Female								
AP	173.88	NA	370.96	223.4	268.46	369.85	459.66	557.02	386.3
ASS	98.19	132.68	106.34	111.8	123.5	155.11	393.81	405.54	298.64
MANI	175.77	NA	167.94	174.85	191.3	198.94	251.32	457.01	316.03
MEGA	66.21	109.5	124.23	171.88	122.39	189.19	259.12	486.57	262.1
MIZO	NA	NA	201.98	243.99	250.84	416.89	390.36	542.05	393.55
NAGA	101.84	NA	NA	130.4	263.93	425.65	553.02	624.98	491.08
SIKK	157.52	NA	149.84	160.93	236.67	488.47	343.57	531.78	386.15
TRIP	89.11	84.68	75.02	110.19	142.92	254.64	227.11	352.77	187.01
NER	129.36	104.94	121.13	141.53	156.7	226.39	368.75	447.35	309
All India	110.83	181.66	127.8	123.81	148.04	190.65	281.6	478.06	300.94

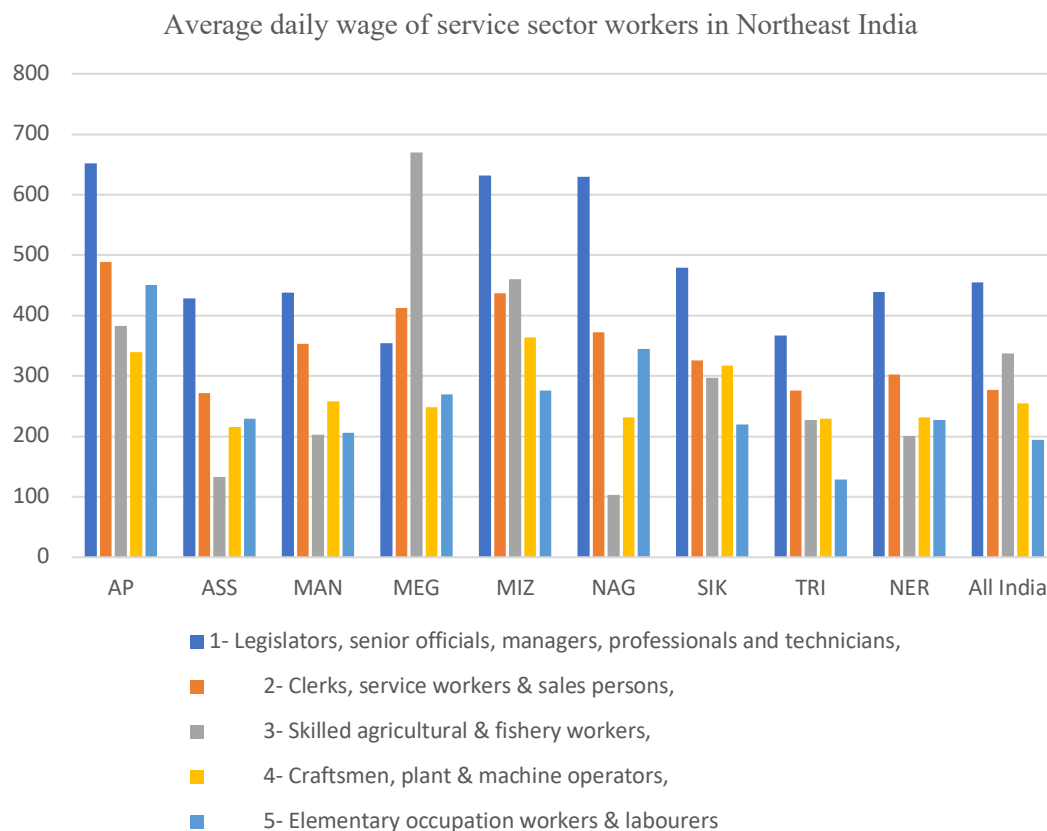
Note: 1-iliterate, 2-literate, 3-Literate without formal schooling, 3-below Primary, 4-Primary
5-Middle, 6-Secondary, 7-Higher secondary, 8-Graduate and above

Source: Authors' calculation from NSS PLFS in 2019-20

Table 6: Average daily wages of worker in the service sector in 2019-20 at 2011-12 constant prices by sex and occupation in Northeast India

Sex	Male					Female				
State/ Occu pation	1	2	3	4	5	1	2	3	4	5
AP	761.92	509.43	442.07	345.72	507.11	398.29	390.01	221.13	176.9	144.93
ASS	459.43	281.12	132.68	215	225.99	337.87	175.03	NA	221.08	389.29
MANI	476.61	402.28	203.14	257.58	239.63	394.3	216.14	NA	293.04	174.09
MEGA	433.46	438.17	705.3	248.65	295.3	246.61	338.54	640.8	64.08	236.03
MIZO	677.92	500.71	441.34	367.25	308.42	515.23	334.94	580.88	231.42	242.74
NAGA	642.97	375.77	NA	231.71	618.99	609.23	354.94	103.18	NA	172.05
SIKK	512.57	326.43	1011.52	281.39	220.77	432.22	325.6	224.36	661.93	215.4
TRIP	464.91	299.17	226.84	229.35	162.78	213.12	183.81	NA	165.15	91.49
NER	478.79	313.74	182.14	230.71	236.6	349.35	230.49	284.56	281.92	183.34
All India	480.48	291.28	349.08	256.69	213	382.26	209.35	161.64	162.71	133.4

Note: 1- Legislators, senior officials, managers, professionals and technicians,
2- Clerks, service workers & salespersons
3- Skilled agricultural & fishery workers
4- Craftsmen, plant & machine operators
5-Elementary occupation workers & labourers
Source: Authors' calculation from NSS PLFS in 2019-20



Note: AP= Arunachal Pradesh, ASS=Assam, MAN=Manipur, MEG=Meghalaya, MIZ=Mizoram, NAG=Nagaland, SIK=Sikkim, TRI=Tripura, NER- Northeastern Region of India Source: Authors' calculation from NSS PLFS in 2019-20

Figure 1: Average daily wage of worker in the service sector in 2019-20 at 2011-12 constant prices by occupation in Northeast India

Considerable inter-state variation is observed in service-sector wages. Mizoram and Sikkim consistently exhibit higher wages (both gender) across most sub-sectors, whereas Tripura and Arunachal Pradesh report relatively lower wage levels, particularly in THR and OTH. Assam shows a mixed pattern, with higher wages in formal service sub-sectors such as FBI and PAD, but lower wages in THR and OTH. The total service-sector wages in the region are found below the national average although the gap is narrower for male, which indicates the relatively lower overall wages in the service sector in Northeast India, despite higher wages in a few

selected sectors. Findings reflect the segmentation of the service sector in Northeast India, which is characterized by significant wage differences across sub-sectors, states, and gender. the formal service activities such as banking, public administration, and education & health offer higher wages, a large share of services employment remains concentrated in lower-paying activities. Wage differentials are further evident when educational levels and occupational groupings are considered. These are shown in tables 5 and 6 and figure 1 (reported only for 2019-20 due to space constraint). Wages increase with higher levels of education, with the highest

earnings evidenced among workers with graduate and above qualifications, besides a gender wage gap. Differences in wages are also apparent across occupational groups, as illustrated in Figure 1, with the highest wages recorded for legislators, senior officials, managers, professionals, and technicians.

CONCLUSION

The analysis of wage patterns in Northeast India shows that despite the significant rise of the real average daily wages since the post-liberalization period, the growth has been uneven. Clear differences across sectors remains, where the primary sector offers the lowest wages, especially in rural areas, whereas the secondary and tertiary sectors (particularly in urban areas) provide better and higher pay. The continued rural-urban wage gap suggests that non-farm employment has not spread widely into rural areas. Within the service sector, wages vary widely across sub-sectors. Formal services such as banking & insurance, public administration & defence, and education & health services offer higher wages. Other trades such as hotels, restaurants, and other personal services remain under compensated. It reflects a dualistic nature of service sector growth. Moreover, gender wage disparity is also evident across sectors, education levels, and occupations. Despite improvements in women's wages, a gender wage gap persists, with women earning lower than men, even in higher-skilled and professional occupational roles that shows the existence of the structural barriers in the society. Wages are also found varying by occupation, with professionals and managers earning much more than clerical and elementary workers. Differences across states are equally evident, with Mizoram, Nagaland, and Sikkim recording higher wages, while Assam and Tripura fall behind in the same. While the expansion of higher-paying service activities has improved average wages, a large segment of the work force remains engaged in low-paid sectors and occupations, particularly women. The

findings have important economic implications, particularly since wage disparity significantly influence economic inequalities and restricting development in rural areas. Addressing these disparities is crucial for the balanced economic development covering rural and urban areas to ensure the development of the region. This draws attention to the necessity of policy makers to promote quality employment generation, reduce occupational segregation, and address gender-based wage inequality by ensuring improved access for women to high-paying service occupations, and reducing rural-urban and interstate disparities.

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ETHICAL APPROVAL

Since the study is based on publicly available secondary data from National Sample Survey Office (NSSO), MOSPI, Government of India, and not on direct surveys/ intervention, or on human or animal experiment. No direct interaction or experiment with human participants were involved.

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A study of production and marketing practices by Handicraft artisans at Pynursla block of Meghalaya

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ABSTRACT

Several studies have examined the impact of handicrafts in the Meghalaya State. But there is a lack of focused research over the handicraft industry particularly at Pynursla block level. The present study seeks to address this gap by examining the production and marketing aspects of handicrafts in selected villages of Pynursla Block, thereby providing insights into the sector's role in sustaining rural livelihoods and preserving cultural heritage. It is a descriptive research design based on primary data collected from 52 artisans, residing at seven different villages falling under Pynursla Block. A structured questionnaire originally prepared in English and later translated into Khasi was used as research instrument. Outcomes suggest that handicraft production in Pynursla Block has not yet evolved into a commercially sustainable livelihood. The artisans are able to preserve their rich cultural heritage through production. There is also a lack of proper market and marketing technique mainly due to pre-defined set of customers mostly locals and middle-men

KEYWORDS: Handicraft, Production, Marketing, Meghalaya

INTRODUCTION

Handicraft symbolises articles made by hand using traditional skills and simple tools. It reflects the creativity, indigenous knowledge, and cultural identity of local communities while also serving functional and aesthetic purposes (Sarma, 2008; Sharma, 2014). It is predominantly a labour-intensive industry that is largely dependent on traditional techniques, locally available raw materials, and household-based units. It occupies a vital position in India's rural economy by generating employment, preserving cultural heritage, and contributing to export earnings.

An interlinkage between production and marketing is pertinent to the handicraft industry and has been highlighted in several studies exhibiting a link between production constraints and marketing challenges. For instance, Dash and Mishra 2021, observed that skills required for design innovation, quality

standardization, and cost-efficient production are lacking among artisans. This limits their ability to place the¹ products effectively both in domestic and in international markets. They also face difficulties in procurement of raw materials, product distribution and pricing due to poor infrastructure as well as dominance of intermediaries who take away a substantial share of profits, resulting into less earnings and further less incentive to improvise upon production process (Dalal et al., 2024). Few more constraints are unorganized marketing systems, financial constraints, and the lack of branding and packaging facilities (Megha, 2019). Currently a growing proportion of craft enterprises are making use of social media platforms such as Facebook and Blogs to promote their craft items; although inadequate digital literacy and lack of training constraint

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the widespread adoption of these tools (Guha. et. al, 2021).

Production and marketing challenges are also pronounced in North-Eastern part of India. They may be categorized into general issues- such as weak branding and limited technology adoption; and region-specific issues related to raw materials, finance, and market access (Sengupta et al., 2020). Studies related to the state of Assam, reveal that handicraft products are tailored to meet market demand (Sarma 2008). However, lack of technological innovation and market intelligence both continues to constrain the bamboo handicraft industry, (Phukan, 2018). In Meghalaya the handicrafts are deeply embedded with tribal traditions serving both utility and decorative purposes (Arunkumar et al. 2012). But handicraft production here still remains largely unorganized and seasonal. It has remained a secondary activity after agriculture. (Tynsong et al., 2020). An absence of systematic marketing channels and limited training facilities related to designing and packaging also restrict the value addition, consequently effecting income of artisans (Lynser et al., 2014). There is also an absence of product customization as tourists demand artistically designed products, whereas the local artisans prefer to make more of utility items, reflecting a mismatch between productions focus and market segmentation. Dasgupta & Sen (2013). This paper is prepared on the basis of Primary Data Survey conducted across 7 villages of Pynursla Block located in the East Khasi Hills District of Meghalaya. This region predominantly inhabited by the Khasi tribe and is well known for bamboo and cane crafts. According to the Meghalaya Pynursla Intelligence Report (Balipara, 2024), about 10% of the population in Pynursla Block is directly engaged in handicraft activities. These crafts not only preserve traditional skills but also generate employment and income (Tynsong et al., 2020). However, no research is evidenced examining the combined effect of production and marketing upon the artisans'

here. This critical research gap is addressed here by examining the production and marketing aspects of handicraft industry through a primary data survey at Pynursla Block of Meghalaya. The present study aims to examine the status and role of the handicraft industry in Pynursla Block of East Khasi Hills District, Meghalaya, with particular emphasis on production, marketing, and livelihood aspects. The objectives of the study are:

- i. To study the demographic variables of artisans with reference to their gender and age
- ii. To identify the major raw materials and production techniques used by artisans in the study area.
- iii. To analyse the customer base and promotional mechanism used by artisans in Pynursla Block for marketing their handicraft products.

METHODOLOGY

This study is a descriptive research design based on primary data collected through direct personal interviews conducted between the period of August and October 2025. Sample selection made through simple random sampling method comprising of 52 artisans both registered and unregistered, residing in seven different villages falling under Pynursla Block. A structured questionnaire originally prepared in English and later translated into khasi language to provide ease of language and better understanding among respondents, was used as research instrument. It covered aspects related to demographic profile, production techniques and marketing of product. Due to limited access of internet facilities in rural areas the questionnaire was printed and data collected through direct administration i.e., face to face interview with respondents.

Responses were systematically organised and tabulated for analysis using MS Excel. Descriptive statistical tools such as frequency and percentage were used for data summarization, identifying the number of observations and facilitate comparison among groups. Bar graphs and pie charts were used to

make visual presentations of raw data, providing an aggregate view of variables.

RESULTS

Out of the seven villages surveyed, Tangmang Village have the highest number of respondent artisans engaged in handicraft production (38.46%) followed by Mawlam Village (34.62%), Pungweikyian Village has 13% of the respondents, Korblang, Nongshken and Wahumleñ village covered 3.85% each. Lastly Myllat Village has the least number of respondents forming only 1.92% of the total respondents. Outcomes are presented under various sub-sections below.

A. Demographic Profile

Demographic profile presents the aggregate statistical summary of the respondents based on characteristics such as age and gender of the artisans. Data collected from the artisans of Pynursla Block reveal that majority of the artisans (around 67%) are not registered, whereas only 33% artisans were registered with the Government and some Government agencies. There is no uniformity in gender representation as more than 88.5 % of the respondents are female; whereas, only 11.5% of the respondents are male artisans, which is also an indication that this sector is female dominant.

Figure 1 below shows that the majority of respondents belong to the age group of 25 to 50 years, accounting for 65% of the total sample. This indicates that the study is largely represented by the economically active and working-age population, who are more likely to have informed opinions and practical experience related to the subject of the study. Respondents aged between 50 to 75 years constitute 31%, reflecting a substantial participation from older adults who may contribute valuable insights based on their experience. There is a limited involvement of teenagers and youngsters in this profession with only 4% of respondents are of up to the age of 25. The findings suggest artisan's age is an important determinant factor and are mainly

influenced by middle-aged and older respondents.

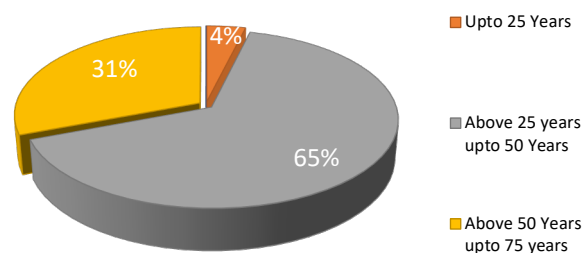


Fig. 1: Age group profile of respondents. Data Source: Primary Data Survey

Gender-wise distribution of respondents across different age groups is depicted in Figure 2 below. Within the age group below 25 years, there are no male respondents, and has only 2 female respondents. In the age group of 25 to 50 years, the number of male respondents (4 nos) is again less as compared to female respondents (30), indicating a stronger female participation. Yet again the 50 to 75 years category has a smaller number of males (2) as compared to females (14).

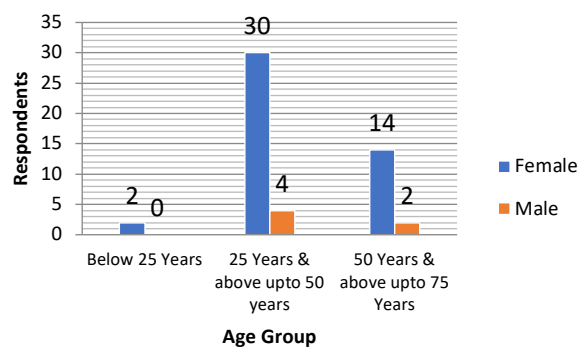


Fig. 2: Age Profile of Respondents (T-Value =1.63, P-Value=0.18, Not significant @5% level), Data Source: Primary Data Survey

In general, the findings advocate a gender imbalance with female respondents dominating across all age groups. This may influence the overall findings and perspectives of the research and are more likely to be influenced by female insights.

B. Production:

In handicrafts, the term production and techniques refer to the various types of Handicrafts items/ products of different designs which these artisans make by using their skills; and the various mechanisms and tools used by them to manufacture such items. In this section the second objective has been analysed, i.e., to study the production techniques and mechanisms. It is sub divided into sub - sections namely, Handicraft items manufactured, Techniques of production, Innovation and design, Time taken, Raw materials and training.

B.1. Handicraft items manufactured

Goods produced by the artisans are mainly traditional in nature, the production process of which they have learned from their ancestors and elders in the family as well as through training mechanism.

Table 1: Products made by artisans

Product manufacture	No. of Respondents	Percentage
Basket	7	13%
Basket and other	14	27%
Basket, Jewellery and other	8	15%
Basket, furniture, Jewellery and other	1	2%
Basket and Jewellery	1	2%
Jewellery	2	4%
Others	19	37%

Data Source: Primary Data Survey

Table-1 above shows distribution of artisans based on the type of products manufactured. Out of 52 respondents around 13% stated that they are making Basket only and concentrate on manufacturing baskets of various types like Betel nut basket, rectangular basket (locally known as Polo), Close weave basket (locally known as Khoh) among others. When combined with basket related production, the figure is significant with 31 artisans (63%) engaged in basket making either exclusively or in combination with other products, indicating

that basket-making remains a dominant traditional craft activity among the respondents. A group of artisans also make multiple products. 27% of the respondents stated that they are making Basket and other products (Mat, Cushions, and Coasters). Around 15% of the respondents make Basket, Jewellery and other products. Additional 2% make Basket and Jewellery, whereas remaining 2% stated that they make basket, furniture, jewellery and other items. Almost all the artisans are involved in basket making along with jewellery, furniture and other handicrafts items. Majority of the respondents (37%) are making other handicraft items such as Cushion, Coasters, Tray, Winnowing Fans, Flower baskets and Trap. 4% of the respondent artisans make only Jewellery and the handicraft items manufactured by them include Earrings, Necklaces and Headgear (Traditional Khasi Crown) out of bamboo.

B2. Raw Materials:

Raw materials refer to unprocessed product which the artisans and craftsmen transform into unique piece of sculpture. Basically, materials from nature such as Bamboo, Cane, wood, leaves, etc., are being used since ages by artisans and craftsmen to create beautiful and unique pieces of handcraft product and are also a part of their tradition. During the survey it has been found that, majority of the artisans use 'Bamboo' and 'Cane' as their prime of raw materials. In addition, they are also using leaves and woods while making products such as Rain shields.

Findings at Table 4 above show that artisans obtain raw materials from multiple sources, i.e., training institutes, local markets, outside village markets and their own farms. Out of the 52 artisans surveyed, 13 artisans (25%) stated that they acquire raw materials through training institutes and organisations. Again, another group of 13 artisans (25%) stated that they purchase raw materials from both local (within village) market and outside village markets.

TABLE 4: Procurement Of Raw Materials

Sources of Procurement	Percent
Purchased through training Institute and organisation	25%
Produced in own Farm	17%
Purchase from local market	8%
Purchase from local market and Outside village	25%
Partially from own field and partially through outside village purchase	13%
Partially from own field and partially purchased from local market	8%
Purchase from local market and have our own raw material	4%

Data Source: Primary Data Survey

About 9 artisans (17%) stated that they use raw materials produced in their own farms, indicating self-reliant. 4 artisans (8%) depend solely on the local market for raw materials. Further, 7 respondents (13%) obtain raw materials partly from their own fields and partly from outside village purchases. Remaining 4 artisans (8%) combine their own field production with purchases from local market. Thus, many respondents depend on multiple sources for procuring raw materials that means they face challenges in obtaining sufficient raw materials from a single source. So, they combine self-production with market purchases to meet their production needs effectively. Hence the artisans first try to fulfil their requirements for raw materials from their own sources of production. Those who are not self-sufficient and those who do not have their own sources are purchasing raw materials form market or organisation(s). One noticeable aspect is that most of them procure raw materials from local sources and are not dependent in any outside region for their supply.

B.3. Time Taken:

Time taken refers to the time devoted each day for affecting the entire process, i.e., moving the raw materials through the entire production process from start to finish, till it gets the final product shape ready for consumption or marketing. As may be seen in Figure 3 below, a large proportion of respondent artisans (46%) devote more than 12 hours per day, followed by

the next group of respondent artisans (38%) who devote 6-12 hours per day. Therefore, a clear indication that handicraft production is highly time-consuming. It is also a labour-intensive activity with want of manual skills. A smaller share of 10% stated that they spend 2-6 hours per day with remaining 6% saying that they spend less than 2 hours per day reflecting that for this group of respondent's handicraft activity may not be the primary activity. The fact that close to half of the respondents are working for more than 12-hours a day reflects the labour-intensive nature of handicraft work with reliance upon manual skills.

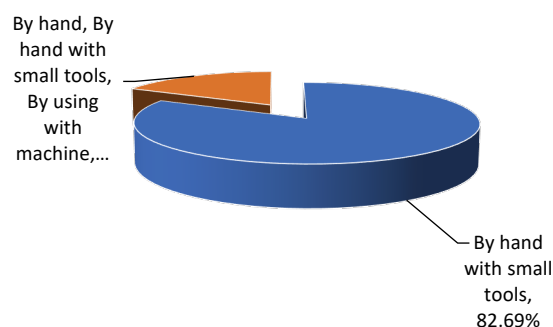


Fig 3: Time Spent per day in making Handicraft Items. Data Source: Primary Data Survey

B.4. Techniques Used

Technique is a method of converting raw materials into output that involves practical skills and the usage of tools and can be classified into labour-intensive and capital-intensive methods. Figure-4 below provides an overview of the tools and techniques used by these respondent artisans. It is observed that a substantial majority of the respondents (82.69%) rely on manual techniques using small hand tools only. Some of the small tools used by them are cutting machine, knife, scissors and saw. In contrast only 17.31% of the artisans use a combination of methods which includes hand work, hand tools and machines. There is a clear dominance of traditional; labour-intensive production techniques among the artisans surveyed reflect the culture of traditional skills and craftsmanship. A minimal usage of modern machine is an indication that

modernisation is not yet prevalent in this sector. This highlights the impact of maintaining the ethnic skill-based value of artisanal work.

B.5 Innovation

Innovation is an essential component of production as it develops something unique in its offerings to customers. Figure 4 shows that 52% of the respondents stated

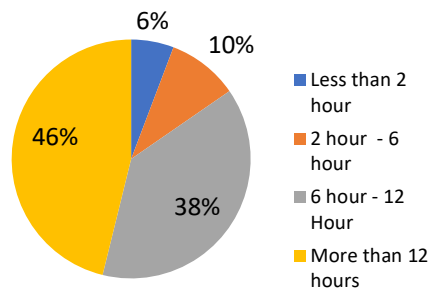


Fig 4: Tools Used for Making Craft Items. Data Source: Primary Data Survey

‘No’ to the question of innovation, while 48% responded ‘Yes’, depicting approximately half of the respondent artisans have engaged in some form of innovation or design modification. A marginal dominance of artisans who do not innovate indicates an inclination towards established pattern of production and may be linked to limited knowledge about market trends with a strong preference in protecting traditional designs. Conversely, a significant proportion of 48% artisans adopting new designs and mechanisms are also an indication of a gradual shift towards innovation. Possible explanations are customer demand, competition or external support through exhibitions or training programmes.

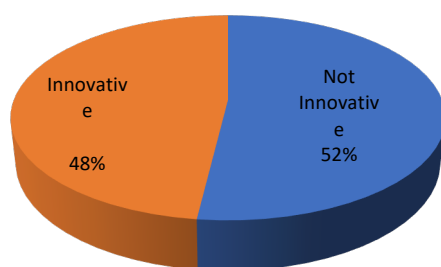


Fig 5: Innovative or Not Innovative. Data Source: Primary Data Survey

Overall findings advocate the existence of traditional practices with emergent openness to innovate, indicating an acceptance of adaptability of new design development and capacity building initiatives required to enhance sustainability and competitiveness. There are some innovations taking place in the manufacturing process of handicrafts, but that is not a striking factor.

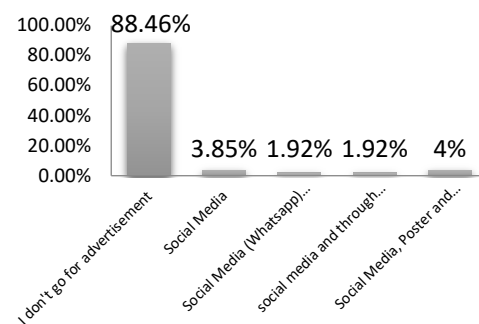


Fig 6: Advertisement & Publicity. Data Source: Primary Data Survey

C. MARKETING

Marketing of Handicraft product is important because it is a means to take the finished products to final consumers. By providing good quality product it will attract customer and helps in preserving the cultural heritage of the handicraft product made by the artisans of the state.

In this section the third objective is being analysed the customer base and promotional mechanism used by artisans in Pynursla Block for marketing their handicraft products. Analysis of customer base is important because the customers drive revenue making them essential for the survival and growth of business. Business houses study customer behaviour to tailor their products and improve services. Again, advertising is also important as it acts as an influencer for customers to purchase their product.

C.1. Customer Base:

Customers are another crucial element for selling products and revenue generation. They are the essential elements for growth and survival of any business. Table 5 below, shows that the local customers form the main

component of customer base; with a significant proportion of 37% of the respondent artisans stating that for the sale of products they are solely dependent on local people (i.e., villagers) only.

Table 5: Customer Bases for Handicraft Production

Types of Customers	Percent age
Local people	37%
Local People, others and if someone is ordering	2%
Local people and middlemen	10%
Local people, middlemen and other	6%
Local people, Tourist and other	2%
Middlemen	6%
Local People & Others	57%
Middlemen and other	8%
Middlemen, Other (when we get order)	25%
Other	2%
Middlemen & Others	27%
Outsider	2%

Data Source: Primary Data Survey

This combined with varied sources reaches up to 57% meaning additional 20% also have local customer base in blend with other sources that are from outside the village. For 8% of the respondents, middle-men and others are the sole customers. When combined with other categories (such as local people or order-based buyers), they represent a larger proportion, including 25% who sell to middlemen and others when orders are received. A heavy dependence on middleman also in combination with other categories of customers suggests a limited direct access by artisans to wider markets.

This not only reflects the artisans' requisite for assured sales channel and market connectivity but also a 'reduced bargaining power and profit margins. A Smaller proportion (2%) reported having customers such as tourists, outsiders and other occasional buyers point towards the untapped potential of expanding market reach through other means like tourism promotion, exhibitions and digital platforms.

C.2. Advertisement:

Advertisement of handicraft products educates the consumer about the materials, process, and proper care of the product that adds to the perceived value of these goods. But the response of artisans depicted in Figure 6 below demonstrates a different attitude towards advertisement.

A vast majority of respondents (88.46%) do not engage in any form of advertisement. Remaining 11.54% respondents' make limited use of promotional methods such as social media (3.85%), WhatsApp and exhibitions (1.92%), social media and promotion through friends (1.92%), and social media, posters and exhibitions (4%). This may be linked to demand and sale of products with more to local customers. There is a minimal use of formal or structured advertising channels that is extremely limited. These restraints can be associated with lack of digital literacy, limited access to technology, financial limitations or even insufficient knowledge about marketing strategies.

DISCUSSION

This study presents some important understandings about the production and marketing dimensions of the handicraft sector in Pynursla Block of East Khasi Hills District, Meghalaya. The outcomes highlight that handicraft production continues to be deeply embedded with traditional practices and strong cultural significance acquired through inter-generational inheritance of skills. Data collections constraint from the artisans is one of the challenges such as limited access or response bias with 52 artisans. The limited sample size may also affect the generalisation of the findings.

Objective 1, i.e., to study the demographic variables of artisans with reference to their gender and age; shows a clear dominance of female artisans across all age groups which indicate that handicraft production is playing an important role in women's economic participation and household sustenance. This is

evident across all age groups. Additionally, the artisan's age is an important determinant factor with more representation from middle-aged and older respondents denoting economically active and working-age population. A limited involvement of younger generation, particularly below 25 years of age marks a gradual disengagement of youth from traditional crafts possibly due to want of modernisation, low return and availability of alternate livelihood options. This also is a cause of concern about the long-standing and sustainability of this sector.

Objective 2 i.e., to study the production techniques and mechanisms; unveils that the artisans are mainly dependent on the traditional methods and techniques in producing the Handicraft Items. Majority make use of small tools and equipment with a negligible usage of modern and electronic gadgets. Time taken to manufacture goods is higher and goes even up to 12 hours of work each day making only limited quantity; is an indication that they give preference to quality over quantity. Innovation in production is not a striking factor. For raw materials, which are mainly bamboo and cane, they are dependent on multiple sources from production in farm to procurement through institutes and markets. So, these artisans are preserving their tradition of manufacturing process that are inherited through training given by elders and others in the same profession and from within the village community only.

Objective 3 i.e., the customer base and promotional mechanism used by artisans in Pynursla Block for marketing their handicraft products, unveils a narrow customer base as most of them have local village people and middle-men as the primary buyers for their products. The predominance of customers from inside and nearby locality as well as middlemen reduces the need for active advertising, as sales is mostly dependent on familiar, adjacent, or order-based channels rather than on competitive and open markets.

All the findings above clearly indicate that handicraft production in Pynursla Block has not

yet evolved into a commercially sustainable livelihood activity. These are corresponding to the ones made by Dasgupta & Sen, 2013; Lynser et al., 2014; Roy, 2016; and, Tynsong. et. al, 2020; in their respective works piloted earlier and in other parts of Meghalaya state. However, the presence of skilled artisans, availability of raw materials, and gradual openness to innovation suggest a stronger potential for development. So, to ensure the long-term sustainability of this sector, there is a need for targeted interventions focusing on skill upgradation, design innovation, access to modern tools, and capacity building in marketing and digital literacy. There also is a need to go for systematic marketing, make more use of electronic media like open their own websites and make thorough advertisements. Furthermore, strengthening institutional support, improving market linkages and encouraging youth participation are also crucial for revitalizing the handicraft industry in this region.

CONCLUSION

The Handicraft Industry in Pynursla Block is culturally rich one driven by skilled artisans and abundant natural resource; has not grown to become a primary source of income. The primary focus is on making products related to daily usage and decorative items using traditional production practices with cane and bamboo as the chief input(s). There is more of female participation those who are also engaged in making handicraft products mainly baskets along-side their other jobs.

The handicraft sector in Pynursla also faces constraints on account of inadequate production capacity, limited market access, dependence on intermediaries, and inadequate institutional support in production and marketing; which further restrict the potential of artisans to expand production and get access to wider markets. Using leveraged institutional support, adopting modern marketing strategies, and fostering product innovation, Pynursla handicraft sector can switch into a more organized and sustainable enterprise,

empowering its artisans and preserving valuable local traditions

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CONFLICT OF INTEREST We declare that there is no Conflict of Interest related to the publication of this work.

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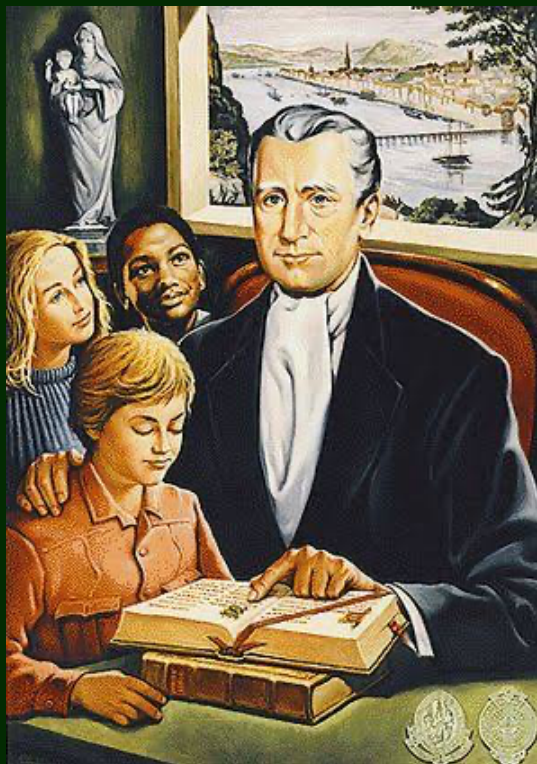
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