Proceedings of Jaffna Science Association

Presidential Address
Chief Guest's Address
Sectional Chairpersons' Addresses
Popular Lectures
Theme Seminar Presentations

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Thirtieth Annual Sessions

12 - 14 July 2024

Jaffna, Sri Lanka

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Editors' Note

It is with great pleasure that I present this volume (Volume 30, No. 2) of the Proceedings of the Jaffna Science Association, a reflection of our enduring commitment to fostering scientific dialogue and intellectual growth in the region.

This edition brings together key contributions from the 30th Annual Scientific Sessions, held from the 12th to the 14th of July 2024 at the Hoover Auditorium. Included within these pages are the Presidential Address, the prestigious Professor Kandiah Balasubramaniam Gold Medal Lecture (Chief Guest's Address), Chairpersons' Addresses, and insightful presentations delivered during Theme Seminar. While the addresses reflect a range of perspectives and expertise, the Theme Seminar presentations specifically focus on the 2024 theme: **"Eco-Innovation Towards Sustainable Development."** These sessions were organized by the thirtieth executive committee of JSA.

Since its establishment in 1991 by the late Professor A. Thurairajah, the Jaffna Science Association has worked tirelessly to nurture scientific thought and disseminate knowledge across the Northern Province. Its initiatives such as School Science Programmes, guest lectures, workshops, seminars, JSA Annual Scientific Sessions, publications of Journals, Magazines and Newsletters continue to inspire and empower a diverse audience of students, academics, and professionals.

It has been a privilege to serve as the editor of this year's Proceedings of the Jaffna Science Association, and I extend my heartfelt thanks to the distinguished speakers for their valuable contributions and kind cooperation in bringing this volume to life.

It is my hope that this volume will serve as a valuable academic resource and a source of inspiration, while also advancing the mission of the Jaffna Science Association in promoting scientific progress and sustainable development.

Ms. Grace H Hensman
Chief Editor/Jaffna Science Association
May 2025

Department of Marketing,
Faculty of Management Studies and Commerce,
University of Jaffna.

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AI for Science and Society
Shaping Our Future in the Northern Province

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Senior Lecturer,
Department of Computer Science,
Faculty of Science,
University of Jaffna, Sri Lanka.

Abstract

This paper, based on the Presidential Address delivered at the 30th Annual Scientific Sessions of the Jaffna Science Association, explores the impact of Artificial Intelligence (AI) on science and society, with a specific focus on its relevance and potential for the Northern Province of Sri Lanka. The paper highlights AI's role in advancing scientific research through faster drug discovery, innovations in materials science, improved climate modeling, more efficient astronomical data analysis, protein structure prediction, and better environmental monitoring. It also examines AI's growing societal role, including improvements in healthcare delivery, personalized education, creative expression, and industrial transformation. The paper identifies key opportunities for the Northern Province to leverage AI in agriculture, fisheries, education, healthcare, environmental management, and cultural heritage preservation. At the same time, it addresses challenges related to AI accuracy, biases, contextual understanding, implementation costs, accessibility, ethical concerns, accountability, and potential over-reliance. Finally, it outlines a strategic path for the Northern Province to responsibly adopt AI by building local capacity, focusing on regional needs, promoting ethical practices, ensuring cultural sensitivity, and using AI to complement human capabilities for a sustainable future.

Introduction

Artificial Intelligence (AI) represents a profound technological shift, rapidly expanding its influence from theoretical computer science to reshape entire industries, drive fundamental scientific discovery, and alter the fabric of daily life. From the algorithms curating social media feeds to breakthroughs in medical research, AI's impact is pervasive and growing. A clear understanding of AI's capabilities, its vast potential, and the inherent challenges it presents is vital for navigating the complexities of the 21st century. This understanding is particularly crucial for regions like the Northern Province of Sri Lanka, which are poised for development and can strategically harness such technologies.

The Northern Province, with its unique socio-economic landscape shaped by its history and specific developmental needs, is at a critical juncture. The strategic adoption of AI promises to address persistent challenges, foster innovation, and unlock significant growth opportunities. However, realizing this potential requires careful consideration of the local context, including cultural nuances, existing infrastructure, and potential socio-economic risks. This paper, based on the Presidential Address delivered at the Jaffna Science Association's 30th Annual Scientific Sessions in July 2024 (Jaffna Science Association, 2024), examines the multifaceted role of AI in both science and society. It specifically focuses on AI's relevance and potential impact on the Northern Province, exploring opportunities across various sectors while simultaneously highlighting the crucial challenges that must be navigated for responsible and beneficial AI integration. The global discourse on AI is extensive; the particular value here lies in contextualizing these global trends and technologies to the specific realities and aspirations of the Northern Province, thereby providing a tailored perspective on how this transformative technology can be best utilized for regional advancement.

The Journey of AI: From Concept to Reality

The ambition to create machines exhibiting intelligence is not a recent phenomenon; it dates back several decades, fueled by science fiction and foundational theoretical work. Alan Turing, a pioneering mathematician and computer scientist, stands as a foundational figure in this journey. His 1950 paper, "Computing Machinery and Intelligence," explored the question of whether machines could think and introduced the concept of the Turing Test, an imitation game to assess a machine's ability to exhibit intelligent behavior indistinguishable from that of a human. This work provided a crucial theoretical underpinning for the nascent field of AI (Turing, 1950).

The formal birth of AI as an academic discipline is widely marked by the 1956 Dartmouth Summer Research Project on Artificial Intelligence. This workshop, organized by John McCarthy, Marvin Minsky, Nathaniel Rochester, and Claude Shannon, brought together researchers who shared the belief that "every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it" (McCarthy et al., 1955). This landmark conference not only coined the term "Artificial Intelligence" but also set the agenda for early AI research, which focused on areas like problem-solving, symbolic reasoning, and natural language processing.[1] Early successes, such as the Logic Theorist program developed by Allen Newell and Herbert A. Simon, which was capable of proving mathematical theorems, demonstrated the initial promise of this endeavor (Newell & Simon, 1956).

[1] https://www.coursera.org/articles/history-of-ai

However, the development of AI has not been a linear progression. It has experienced periods of reduced funding and waning interest, famously known as "AI Winters".[2] These downturns often followed periods of high optimism where predictions about AI's capabilities outpaced the then-current limitations in computing power, data availability, and algorithmic sophistication.[3] The complexity of real-world problems, ambiguity in human language, and the sheer computational demands of simulating intelligence posed significant hurdles (Anyoha, 2017).

In recent years, breakthroughs in machine learning, particularly deep learning, have dramatically reshaped the AI landscape. The confluence of massive datasets (Big Data), significantly increased computational power (largely due to advancements in Graphics Processing Units - GPUs), and the development of more sophisticated algorithms has fueled a powerful resurgence. Machine learning allows systems to learn from data without being explicitly programmed for each task. Deep learning, a subfield of machine learning, utilizes multi-layered artificial neural networks to model complex patterns in data, leading to remarkable progress in areas such as image recognition, speech processing, and natural language understanding. This cyclical pattern of ambition, initial breakthroughs, periods of disillusionment, and subsequent resurgence driven by new technological enablers suggests that while current AI capabilities are impressive, the field may continue to evolve in response to new challenges and innovations.

Today, AI is deeply integrated into our digital infrastructure and is increasingly impacting the physical world. Its applications are widespread and often invisible:

- **Search Engines:** AI algorithms power search engines, enabling them to understand user intent and rank information effectively.
- **Email Filters:** AI is used to filter spam and categorize emails, improving productivity.
- **Virtual Assistants:** Voice-activated assistants like Siri and Alexa use AI to understand and respond to natural language commands.
- **Recommendation Systems:** Platforms like Netflix and Amazon use AI to analyze user behavior and provide personalized recommendations for content and products.
- **Conversational AI:** Advanced tools like ChatGPT can generate human-like text, engage in complex conversations, and perform a variety of language-based tasks. These examples illustrate AI's significant transition from a futuristic concept to an indispensable technology that shapes our daily interactions and information consumption, underscoring the need for broader societal understanding and governance of its pervasive influence.

[2] https://www.techtarget.com/searchenterpriseai/definition/AI-winter
[3] https://ojs.aaai.org/aimagazine/index.php/aimagazine/article/view/494/430

How AI is Revolutionizing Science

The scientific method, traditionally involving observation, hypothesis formation, experimentation, and analysis, is being profoundly augmented by Artificial Intelligence. AI serves as a revolutionary tool across these stages, accelerating the pace of discovery and enabling scientists to tackle problems of unprecedented complexity. Its capacity to process and analyze massive datasets, identify subtle patterns often missed by human researchers, and even generate novel hypotheses is transforming research paradigms across numerous disciplines. This shift towards more data-driven and AI-assisted scientific exploration signifies a fundamental change in how scientific knowledge is generated and validated.

AI's impact on science is evident in several key areas:

- **Accelerating Drug Discovery and Development:** AI significantly speeds up the drug discovery pipeline. It can analyze vast libraries of chemical compounds, predict their potential properties and efficacy, simulate molecular interactions, and identify promising candidates for further testing.[4] This *in-silico* (performed on a computer or via computer simulation software) screening reduces the time and cost associated with extensive laboratory work. For instance, AI has been instrumental in identifying potential new antibiotics against drug-resistant bacteria, a critical global health challenge (Elalouf et al., 2025; Yönden et al., 2025). A landmark achievement in this domain is AlphaFold, an AI system developed by DeepMind,[5] which can predict the 3D structure of proteins from their amino acid sequences with remarkable accuracy. This is crucial for understanding protein function, disease mechanisms, and identifying targets for new drugs (Jumper et al., 2021).
- **Materials Science and Discovery:** In materials science, AI algorithms analyze extensive databases of known materials to identify complex relationships between their atomic structure and functional properties. This allows scientists to predict the characteristics of novel materials and even design materials with specific desired attributes from scratch, thereby accelerating the discovery of new materials for applications in renewable energy (e.g., batteries), electronics, and aerospace composites.
- **Enhancing Climate Modeling and Prediction:** AI is enhancing the accuracy and resolution of climate models by improving the integration and interpretation of vast quantities of data from diverse sources, including weather stations, satellites, and ocean sensors. Machine learning algorithms can identify complex, non-linear patterns in this data, leading to more

[4] https://www.hoganlovells.com/en/publications/ai-use-by-life-sciences-companies-strategic-considerations
[5] https://alphafold.ebi.ac.uk/

accurate simulations of future climate scenarios and more precise predictions of regional impacts (UNFCCC, 2024).

- **Revolutionizing Astronomy and Astrophysics:** The field of astronomy is being transformed by AI's ability to efficiently process and analyze the enormous datasets generated by modern telescopes. AI algorithms can automatically identify and classify celestial objects, detect transient events like supernovae, and find subtle anomalies in data streams much faster and more consistently than human analysis alone. AI also plays a vital role in processing data from gravitational wave detectors and radio telescopes, contributing to groundbreaking discoveries about the universe (Djorgovski, 2022).
- **Unlocking the Secrets of Life: Protein Folding:** As mentioned, DeepMind's AlphaFold system achieved an unprecedented breakthrough by predicting the 3D structures of proteins with high accuracy, effectively solving a grand challenge in biology that had persisted for over 50 years (Jumper et al., 2021). Understanding protein structures is fundamental to deciphering disease mechanisms, developing targeted medicines, and advancing fields like synthetic biology. The availability of accurate protein structure predictions on a large scale is opening up new frontiers in biological research.
- **Monitoring Our Planet and Environment:** AI is a powerful tool for environmental monitoring and conservation. It analyzes satellite images, drone footage, and sensor data to track deforestation, monitor changes in land use, detect illegal fishing activities, and assess biodiversity. AI also aids in predicting and monitoring natural disasters such as floods, wildfires, and landslides, enabling earlier warnings and more effective emergency responses.[6] For example, AI is used to analyze satellite data to track maritime safety and climate change monitoring (Bianchi, 2024).

These examples collectively demonstrate AI's transformative power in scientific research. By automating laborious tasks, analyzing complex and high-dimensional data, and identifying hidden patterns and correlations, AI is accelerating the pace of discovery and enabling scientists to address questions that were previously considered intractable. This synergy between AI and scientific inquiry has direct societal benefits, particularly in medicine and environmental management, creating a virtuous cycle of advancement.

[6] https://aithor.com/essay-examples/the-role-of-ai-in-predicting-and-managing-natural-disasters

AI's Growing Role in Society

Beyond its profound impact on scientific laboratories, AI is increasingly woven into the fabric of society, influencing daily life, human interactions, and even creative expression. This integration is multifaceted, offering transformative benefits in critical sectors while simultaneously posing novel challenges to established norms and practices.

- **Healthcare Transformation:** AI is significantly improving healthcare diagnostics, personalizing treatment regimens, and enhancing overall patient care. AI-powered tools can analyze medical images, such as X-rays and MRIs, with high accuracy to aid in the early detection of diseases like cancer and diabetic retinopathy. AI algorithms analyze vast datasets of patient information to predict individual disease risks and help tailor personalized treatment plans (Kohane, 2024). Conversational AI and chatbots are being developed to assist with initial patient screening, provide health information, and even support diagnostic conversations, showing promising performance in certain contexts.[25] The potential for AI to improve diagnostic accuracy and efficiency, especially in resource-limited settings, is substantial (Adhikari, 2025).[7] AI also has the potential to predict and manage future global disease outbreaks (Harati, 2025).
- **Personalized Education and Skill Development:** AI is enabling more personalized and adaptive learning experiences. AI-powered educational platforms[8] can analyze individual student performance data to provide tailored content, targeted feedback, and customized learning pathways. Virtual tutors offer individualized support, adapting to each student's learning pace and style. As anecdotally observed with a Grade 9 student using ChatGPT for coding assistance (Jaffna Science Association, 2024), AI can be a powerful tool for self-directed learning and exploration. In Sri Lanka, initiatives like the establishment of 'Artificial Intelligence Student Societies' in schools aim to foster early engagement with AI, equipping students with future-ready skills.[9] AI also assists educators by automating tasks like grading and providing insights into student progress, allowing teachers to focus more on direct instruction and support.
- **Enhancing Creativity and Artistic Expression:** AI is emerging as a novel medium for creative expression, with systems capable of generating images, composing music, writing poetry, and even creating elements for films. This has sparked considerable debate about authorship, originality, and the very definition of art (Helliwell, 2024). An AI-generated image winning a prestigious photography award, submitted by artist Boris Eldagsen who then

[7] https://freseniusmedicalcare.com/en-us/insights/gmo-dialogs/ai-in-healthcare/
[8] https://www.khanmigo.ai/
[9] https://slguardian.org/application-of-artificial-intelligence-to-education-in-sri-lanka/

declined the prize to provoke discussion, highlights the sophistication of AI in creative domains.[10,11,12] AI tools can act as collaborators for human artists or generate entirely novel content. The creation of AI-generated Tamil poetry inspired by the style of Mahakavi Bharathiyar, shown below and presented at the Jaffna Science Association sessions, exemplifies AI's potential to engage with specific cultural and linguistic contexts in creative expression.

காலை வெயிலில்
மலைப்பாதை ஏறும் பெண்
விடியும் சுதந்திரம்!

A poem and a line art generated by AI in response to a query to create a poem inspired by Bharathiyar's *Pudhumaippen*.

- **Reshaping Industries and the Future of Work:** AI is a key driver of what is often termed the "Fourth Industrial Revolution," characterized by the integration of digital, physical, and biological technologies. AI-powered automation is transforming sectors like manufacturing, logistics, and customer service, often leading to increased efficiency and productivity. While this automation may displace certain types of jobs, it is also creating new roles related to AI development, deployment, maintenance, and oversight. Consequently, reskilling and upskilling the workforce to adapt to these changes are crucial societal tasks.[13] Industries are leveraging AI for diverse applications, including predictive maintenance of machinery, optimization of complex supply chains, quality control in manufacturing processes, and the delivery of highly personalized marketing campaigns.

The integration of AI into society is a complex and ongoing process. It offers immense potential for improvement across many domains but also raises fundamental questions about the future of work, ethical considerations in AI development and deployment, and the need for responsible governance to ensure that these powerful technologies benefit humanity as a whole. The examples

[10] https://www.newsweek.com/ai-photography-contest-sony-art-1796455
[11] https://www.scientificamerican.com/article/how-my-ai-image-won-a-major-photography-competition/
[12] https://www.forbes.com/sites/lesliekatz/2024/06/13/real-photo-wins-ai-photography-contest/
[13] https://www.weforum.org/stories/2025/04/linkedin-strategic-upskilling-ai-workplace-changes/

above illustrate both the democratizing potential of AI tools and the necessity for cultural specificity and careful consideration of societal impacts for their meaningful and equitable adoption.

Opportunities for the Northern Province

The Northern Province of Sri Lanka, with its distinct socio-economic context and developmental aspirations, stands to gain significantly from the strategic and tailored application of Artificial Intelligence. By focusing on local challenges and leveraging AI to enhance existing strengths, the province can foster sustainable development and improve the quality of life for its citizens. The successful adoption of AI will depend on contextualizing solutions to regional needs, rather than implementing generic technologies. Many successful AI applications in similar developing contexts often involve collaborative efforts between government, research institutions, and other stakeholders, suggesting a pathway for the Northern Province.

Table 1: AI Opportunities for the Northern Province

Sector	**Specific AI Application**	**Example/Model**	**Potential Benefit for NP**
Agriculture	Precision Agriculture (Pest & Disease Detection)	AI analysis of drone/satellite imagery for Fall Armyworm detection (e.g., World Bank Malawi project; GeoGoviya Sri Lanka[14])	Early detection of pests like Fall Armyworm in maize, targeted pesticide use, reduced crop loss, improved food security.
	Crop Yield Prediction	AI models for paddy & onion yield forecasting (Jiya, 2023)	Better farm planning, informed market decisions, stabilized farmer income, enhanced food security.
	Optimized Water Management	AI-driven irrigation scheduling (e.g., Microsoft AI Sowing	Efficient water use, conservation in dry seasons, reduced water wastage, increased crop resilience.

[14] https://www.iwmi.org/blogs/smart-farming-transforms-agriculture-in-sri-lanka/

		App, India[15], and SenzAgro, Sri Lanka[16])	
Fisheries	Sustainable Fish Stock Assessment	AI analysis of sonar/satellite data for species like Trevally, Sprat (e.g., general AI in fisheries[17]; FAO AI for fish quality SL[18])	Data-informed catch limits, prevention of overfishing, long-term sustainability of marine resources.
	Aquaculture Optimization	AI monitoring of water quality, feed management in farms (e.g., Norway's AquaCloud platform[19])	Improved aquaculture productivity, disease prevention, reduced environmental impact, enhanced farmer income.
	Combating Illegal, Unreported, Unregulated (IUU) Fishing	AI analysis of satellite vessel tracking data	Protection of local fishing grounds, conservation of fish stocks, support for legal fishing practices.
Education	Personalized Learning Tools	AI-powered adaptive learning apps tailored to Tamil language & local curriculum.	Improved student engagement, learning outcomes tailored to individual needs, support for diverse learning paces.
	Teacher Support Systems, Specially in the secondary schools.	AI tools for automating grading, suggesting teaching resources (e.g., general EdTech AI)	Reduced teacher workload, more time for direct student interaction and personalized support.

[15] https://news.microsoft.com/en-in/features/ai-agriculture-icrisat-upl-india/
[16] https://senzagro.com/solutions/precision-agriculture/
[17] https://www.fisheries.noaa.gov/feature-story/microsoft-provides-ai-and-cloud-computing-noaa-project-better-map-prime-salmon-habitat
[18] https://www.ungm.org/Public/Notice/229884
[19] https://aquacloud.ai/about

	Vocational Training & Skill Development	AI-driven online platforms for locally relevant job skills (e.g., Sri Lankan AI Student Societies initiative[20])	Enhanced employability, development of a skilled workforce for emerging industries, access to quality training.
Healthcare	Enhanced Telemedicine & Remote Consultation	AI chatbots for initial patient screening, information gathering (However, need to introduce AI for healthcare policies)	Improved access to healthcare in rural areas, efficient use of specialist time, reduced travel for patients.
	Basic Diagnostic Assistance for Rural Health Workers	AI tools analyzing symptoms or basic medical images for initial assessment (e.g., Kohane, 2024 insights[21])	Empowerment of local health workers, faster referrals, improved diagnostic support in underserved areas.
	Public Health Surveillance	AI analysis of health data to predict & monitor disease outbreaks (e.g., Dengue fever)	Early warning for epidemics, targeted prevention campaigns, better resource allocation for public health.
Environmental Management	Optimized Water Resource Planning	AI models integrating hydrological & climate data for water management (e.g.,	Sustainable water allocation, drought preparedness, efficient management of shared water resources.

[20] https://slguardian.org/application-of-artificial-intelligence-to-education-in-sri-lanka/
[21] https://freseniusmedicalcare.com/en-us/insights/gmo-dialogs/ai-in-healthcare/

		UNFCCC report applications[22])	
	Coastal Erosion Monitoring & Prediction	AI analysis of satellite/drone imagery to track coastline changes. The Coastal erosion is a problem in Sri Lanka.	Early identification of vulnerable areas, informed coastal protection strategies, safeguarding coastal communities.
	Improved Waste Management	AI for optimizing waste collection routes, identifying illegal dumping (Tennakoon, 2025)	More efficient waste collection, reduced pollution, promotion of recycling and sustainable waste practices.
Cultural Preservation	Digitization & Transcription of Manuscripts	AI-OCR for Tamil palm-leaf documents (olai suvadi) (e.g., Pradeep, 2024[23])	Preservation of invaluable historical & literary heritage, enhanced accessibility for researchers & public.
	Language Learning & Revitalization Tools	AI-powered applications for learning/preserving Jaffna Tamil dialect	Support for linguistic diversity, tools for younger generations to connect with local dialect.
	Virtual Heritage Experiences	AI-created immersive virtual tours of historical sites (e.g., Nallur Kovil, Jaffna Fort)	Promotion of cultural tourism, educational tool for history, accessible heritage experiences.

[22] https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/tn_meetings/0ec396b0ba7b4d0d853b77c7b83dc172/3ebbf2e8e7834a7f873b0ae9a86262f7.pdf

[23] https://archive.org/details/nandhini-pradeepv-1/NANDHINI%20PRADEEPv1?q=%22advanced+imaging%22

The key opportunities outlined in Table 1 illustrate AI's potential to act as an enabler of sustainable development across multiple interconnected sectors in the Northern Province, also applicable throughout Sri Lanka. For instance, advancements in agricultural AI can bolster food security and the local economy, while AI-driven healthcare improvements contribute to a healthier populace. Concurrently, enhancing education through AI builds the necessary human capital, and AI applications in environmental management ensure long-term ecological viability. The preservation of cultural heritage through AI strengthens community identity and historical continuity. This interconnectedness implies that strategic AI investments in one domain can yield positive externalities in others, fostering holistic regional progress.

These examples illustrate that AI's potential in the Northern Province is vast. However, its realization requires a focused, strategic, and collaborative approach that prioritizes local needs, builds local capacity, and ensures that AI is deployed responsibly and ethically.

Navigating the Challenges: A Word of Caution

While Artificial Intelligence offers significant benefits and transformative potential, its development and deployment are accompanied by inherent limitations and risks that demand careful consideration. A failure to acknowledge and proactively address these challenges can lead to unintended negative consequences, hinder adoption, and exacerbate existing inequalities. For the Northern Province, a region with its own unique vulnerabilities and developmental stage, a cautious and well-informed approach is paramount. The challenges are not merely technical; they are deeply intertwined with socio-cultural, economic, policy, and ethical considerations, necessitating holistic strategies that go beyond mere technological implementation. Key challenges include:

- **Accuracy and Bias:** AI systems are fundamentally limited by the data they are trained on. If the training data is biased, incomplete, or of poor quality, the AI system will inevitably learn and perpetuate these biases, potentially leading to unfair or discriminatory outcomes. For example, an AI system used for loan applications, if trained on historically biased lending data, could unfairly deny loans to certain demographic groups. Furthermore, Large Language Models (LLMs), despite their fluency, can "hallucinate" – generating plausible but incorrect or nonsensical information (Bender et al., 2021). Ensuring data quality, fairness, and developing robust methods to mitigate bias are critical ongoing challenges.[24]
- **Lack of True Understanding and Context:** Current AI systems, even the most advanced ones, operate based on pattern recognition in data rather than a genuine, human-like understanding of the world. They lack common sense, true causal reasoning, and emotional

[24] https://www.ris.org.in/sites/default/files/Publication/DP-296-Anupama-Vijayakumar.pdf

intelligence. As emphatically noted during local discussions, "AI DOES NOT UNDERSTAND OUR CULTURE WELL!" This is a critical limitation, especially in culturally sensitive contexts like the Northern Province, where AI systems may struggle with linguistic nuances, implicit social cues, and local customs. Deploying AI without a keen awareness of these limitations can lead to misinterpretations, culturally inappropriate outputs, and a general disconnect from local realities.

- **Cost and Accessibility:** The development and deployment of advanced AI systems often require significant investment in computing infrastructure (e.g., GPUs), large datasets, specialized software, and highly skilled personnel. These high costs can create barriers to entry, potentially widening the digital divide between those who can afford to leverage AI and those who cannot. For regions like the Northern Province, ensuring equitable access to AI technologies, tools, and training is a significant challenge. Strategies are needed to make AI more affordable and accessible, perhaps through open-source initiatives, shared infrastructure, and targeted capacity-building programs.
- **Ethical Concerns and Accountability:** The increasing integration of AI into society raises a host of complex ethical questions. These include concerns about job displacement due to automation, the potential for increased surveillance and erosion of privacy, and the critical issue of accountability when AI systems make errors or cause harm. Establishing clear ethical guidelines, robust regulatory frameworks, and effective accountability mechanisms is essential to ensure that AI development and deployment align with societal values and protect fundamental human rights.[25] Research into Explainable AI (XAI) aims to make the decision-making processes of complex AI models more transparent and understandable, which is a crucial step towards building trust and enabling accountability (Lundberg & Lee, 2017; Ribeiro et al., 2016). In contexts where trust in technology is still developing, or where AI decisions have significant impacts, the need for transparency and clear lines of responsibility is particularly acute.

Navigating these challenges successfully requires a proactive, multi-stakeholder approach involving policymakers, researchers, businesses, and civil society. It necessitates ongoing dialogue, investment in research to address AI's limitations, and a commitment to developing and deploying AI in a manner that is not only technologically advanced but also ethically sound, culturally sensitive, and socially equitable.

[25] https://asean.org/wp-content/uploads/2025/01/Expanded-ASEAN-Guide-on-AI-Governance-and-Ethics-Generative-AI.pdf

The Path Forward for the Northern Province

The journey of Artificial Intelligence, from its conceptual origins to its current societal impact, presents both remarkable opportunities and significant challenges. For the Northern Province of Sri Lanka, the path forward involves not a blind adoption of AI, but a considered and strategic embrace of its potential, tailored to the unique context and aspirations of the region. This requires a proactive, human-centric approach that emphasizes local ownership, ethical governance, and sustainable development goals, transforming AI from a mere technological tool into a catalyst for positive change.

To responsibly harness AI for a brighter future, the Northern Province should focus on several key strategies:

1. **Building Local Capacity:** A foundational step is to invest in human capital. This includes developing AI literacy across the population and specialized skills in AI development, data science, and AI ethics through educational programs at universities like the University of Jaffna, vocational training centers, and schools. Supporting local researchers and innovators will be crucial for creating contextually relevant AI solutions.
2. **Focusing on Regional Needs:** AI initiatives should be problem-driven, addressing specific challenges and opportunities within the Northern Province's key sectors, such as agriculture, fisheries, healthcare, education, and cultural preservation, as outlined previously. This requires a deep understanding of local needs, resources, and cultural nuances, ensuring that AI solutions are practical, appropriate, and beneficial to the community.
3. **Promoting Ethical AI Development and Deployment:** A strong commitment to ethical principles must underpin all AI initiatives. This involves proactively addressing potential biases in AI systems, ensuring fairness and non-discrimination, safeguarding data privacy and security, and establishing clear lines of accountability for AI-driven decisions and their outcomes. Adopting or adapting responsible AI frameworks, such as those proposed by ASEAN or considering insights from the Global South discourse on AI ethics, can guide this process.
4. **Ensuring Cultural Sensitivity:** Given the rich cultural heritage and specific linguistic context of the Northern Province, AI applications must be developed with cultural sensitivity. This includes ensuring that AI systems respect local customs and values, and that language-based AI tools are proficient in Tamil, including local dialects, to be truly effective and inclusive.
5. **Augmenting Human Capabilities:** The most beneficial applications of AI will likely be

those that augment human intelligence and capabilities, rather than seeking to replace humans wholesale. AI should be viewed as a powerful tool to assist professionals, empower individuals, and enhance decision-making, fostering a collaborative relationship between humans and machines.

6. **Fostering Collaboration and Partnerships:** Successfully implementing AI solutions will require collaboration among various stakeholders, including government agencies, academic institutions, the private sector, community organizations, and potentially international partners. Such partnerships can pool resources, share expertise, and ensure that AI initiatives are aligned with broader development goals.

By pursuing these strategies, the Northern Province can navigate the complexities of the AI revolution, mitigating its risks while maximizing its benefits. The goal is not just to adopt AI, but to shape its application in a way that reflects the region's values, empowers its people, and contributes to a sustainable and equitable future for all its inhabitants. The journey requires foresight, investment, and a collective commitment to harnessing AI for the common good.

அவதானம்
இயந்திரங்களிடம் எம் வலுவைத் தொலைத்துவிட்டோம்!
கணினிகளிடம் எம் செயற்திறனைத் தொலைத்துவிட்டோம்!
நினைவகங்களிடம் எம் மனன ஆற்றலைத் தொலைத்துவிட்டோம்!
வட்சப்பில் எம் பிணைப்புகளைத் தொலைத்துவிட்டோம்!
கூகிள் மைப்புகளில் பாதையைத் தொலைத்துவிட்டோம்!
அவதானம்,
உருவாக்க செயற்கை நுண்ணறிவிடம் எம்மையே தொலைத்துவிடாதிருப்போமாக!

We have lost our strength to machines!
We have lost our efficiency to computers!
We have lost our cognitive power to memories!
We have lost our connections to WhatsApp!
We have lost our way to Google Maps!
Attention,
Let us not lose ourselves to generative artificial intelligence!

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Saving mothers lives from postpartum haemorrhage - 'Revival of Tranexamic Acid'

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Background

Maternal mortality is one of the dreaded events in the field of medicine where a woman loses her life directly or indirectly as result of a pregnancy even though pregnancy is considered physiological. Almost all the countries in the world, health organizations, professional bodies, researchers and individuals who are involved in the care of pregnant women are constantly working to reduce maternal mortality at different levels.

Unprecedented numbers of researches are being conducted around the world in a quest to search for a solution in terms new and management strategies, drugs, devices and surgical techniques to save mothers from dying. Recently an old drug called tranexamic acid (TXA) has been shown to be effective in the treatment of postpartum hemorrhage, which still is a leading cause of maternal mortality worldwide.

The following excerpts I hope will shed light on this almost forgotten drug which has revived itself to save mothers lives after half a century of its intended invention.

Early history of tranexamic acid.

It all started with a Japanese 'wife and husband' team in Tokyo in the 1950s the husband Shosuke Okamoto and the wife Utako Okamoto. At that time Shosuke Okamoto was an associate professor in physiology at Kobe University and Utako Okamoto was a senior lecturer in physiology at Keio University School of Medicine.

This couple were determined to identify a drug that could reduce bleeding during and after childbirth. The couple were morally inclined towards this venture as during this period globally as well as in Japan postpartum hemorrhage was a leading cause of maternal deaths killing almost every 50^{th} mother who delivered a baby.

Their hard work paid off and in 1962, they published in the Keio Journal of Medicine about a drug called Amino-Methyl-Cyclohexane-Carboxylic-Acid (AMCHA) currently known as **tranexamic acid (TXA),** which they discovered to be 27 times more powerful than a previous lysine-based substance. Anyway, no research or trials followed this invention and the drug was virtually ***orphaned.*** An orphan drug is a pharmaceutical agent developed to treat medical conditions which, because they are so rare, would not be profitable to produce without government assistance.

Mode of action tranexamic acid

Hemostasis is the physiological process that stops bleeding at the site of an injury while maintaining normal blood flow elsewhere in the circulation. The endothelium in blood vessels maintains an anticoagulant surface that serves to maintain blood in its fluid state, but if the blood vessel is damaged components of the subendothelial matrix are exposed to the blood.

Primary hemostasis refers to platelet aggregation and platelet plug formation where platelets are activated in a multifaceted process, and as a result they adhere to the site of injury and to each other, plugging the injury.

Secondary hemostasis refers to the deposition of insoluble fibrin, which is generated by the proteolytic coagulation cascade. This insoluble fibrin forms a mesh that is incorporated into and around the platelet plug. Further this mesh serves to strengthen and stabilize the blood clot. These two processes happen simultaneously and are mechanistically intertwined.

The opposite of this, fibrinolysis is a key component of the hemostatic processes that maintain patency of the vascular system. Circulating plasminogen is converted to the serine protease plasmin by the enzyme tissue plasminogen activator (tPA), causing the breakdown of fibrin to fibrin degradation products (FDPs).

The complexity of these systems has been increasingly appreciated in the last few decades.

Multiple anticoagulant mechanisms regulate and control these systems to maintain blood fluidity in the absence of injury and generate a clot that is proportional to the injury.

The proper balance between procoagulant systems and anticoagulant systems is critical for proper hemostasis and the avoidance of pathological bleeding or thrombosis.

Tranexamic acid acts in the fibrinolytic side of this complex system by binding to the 5 lysine binding sites on plasminogen. This binding inhibits plasmin formation and displaces plasminogen from the fibrin surface which is its main mode of action. This prevents the fibrin from breaking down to fibrin degradation products.

Pharmacokinetics

Tranexamic acid which is a synthetic derivative of the amino acid lysine (Figure 1) and it is administered intravenously and orally.

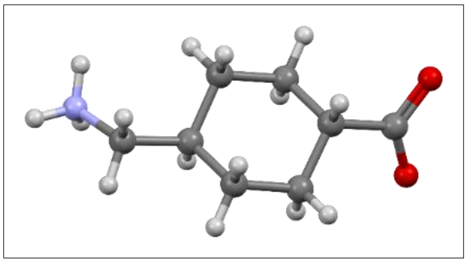

Figure 1: Molecular structure of tranexamic acid

Tranexamic acid is minimally bound to plasma proteins (3%) and binds to plasminogen and there is no apparent binding to albumin.

Only a small amount of tranexamic acid is metabolized and it is eliminated by urinary excretion primarily via glomerular filtration.

Overall clearance is equivalent to plasma clearance (110 to 116 mL/minute) with more than 95% of the dose excreted unchanged.

The elimination half-life of tranexamic acid is approximately 2 hours, and the mean terminal half-life is approximately 11 hours.

Initial recognition of tranexamic acid

Though there were some initial interest in late 60s in using tranexamic acid for heavy menstrual bleeding it was not officially approved for this purpose.

Later during 1980s its oral preparation which was called the 'novel oral formulation' was slowly becoming popular as a treatment for heavy menstrual bleeding and more RCTs were being conducted and published during this time.

The food and drug administration (FDA) first approved tranexamic acid only in 2009 for the treatment of heavy menstrual bleeding.

With growing popularity of its use in heavy menstrual bleeding the *Cochrane Database* in 2018 published its systematic review on the use of antifibrinolytic treatment such as tranexamic acid in the treatment of heavy menstrual bleeding. This systematic review included 13 RCTs with 1312 participants.

Emerging concern of thrombosis

With more evidence emerging about the effectiveness of tranexamic acid, there were rising concerns as to whether it increases the risk of thrombosis in these patients.

This concern was mainly based on its mode of action namely inhibiting the formation of plasmin from plasminogen and thus inhibiting the dissolution of thrombi.

The study group of the Cochrane systematic review that looked at its usefulness in the treatment of HMB was also concerned about this unwanted side effect and they too did look in to this complication.

Cochrane systematic review reported that most studies did not include venous thromboembolism (VTE) as an end-point but studies that did measure VTE have not shown any increase in risk with antifibrinolytic treatment for HMB.

Also, observational, population-based studies on the association between use of tranexamic acid for menorrhagia and VTE showed a negative association between tranexamic acid and VTE.

Further its thrombogenic risk has been extensively researched with all its current uses in cardiac and orthopedic surgery.

Most of the studies concluded that when used after excluding the contraindications with appropriate post-operative precautions there was no increase in the frequency of thrombosis compared to the control groups.

The use of tranexamic acid in hemorrhage due to trauma

By this time antifibrinolytics especially tranexamic acid has gained its place as a drug to reduce intra and post-operative bleeding in cardiac and orthopedic surgery. Several protocols included the usage of tranexamic acid during cardiac and orthopedic surgery and at times it was even used locally at the site of surgery.

Many clinical practice guidelines currently recommend intraoperative use in cardiac and orthopedic procedures and its benefits are well established as an antifibrinolytic with proven efficacy. But it was never routinely used in trauma patients.

The CRASH 2 trial

This large multicenter trial was undertaken by the Clinical Trials Unit of the London School of Hygiene and Tropical Medicine. 274 hospitals in 40 countries participated with a study population of 20,211 adult trauma patients with or at risk of significant hemorrhage, defined based on hemodynamic instability. Enrolment began in May 2005 and patients were randomized to double-blind treatment with either tranexamic acid or a matching placebo, given within 8 hours of presentation. All analyses were done on an intention-to-treat basis and followed up to 4 weeks with endpoint of the study being death in-hospital within 4 weeks of injury.

The results of the much-awaited CRASH 2 trial were published in the Lancet in 2010 and it concluded that tranexamic acid safely reduced the risk of death in bleeding trauma patients in this study. Further they found that:

- There was no apparent increase in fatal or non-fatal vascular occlusive events.
- All-cause of mortality was significantly reduced with tranexamic acid.
- TXA appears most effective when given early after the trauma and should be given only within approximately 3 hours.
- Treatment beyond 3 hours of injury was shown to be ineffective.

It is therefore unsurprising that there was interest in its role in the prevention of postpartum hemorrhage and after all tranexamic acid was originally invented by the Okamoto couple to save mothers from it.

Worldwide trend of maternal mortality and postpartum hemorrhage

The maternal mortality ratio (MMR) is defined as the number of maternal deaths during a given time period per 100,000 live births during the same time period. It depicts the risk of maternal death relative to the number of live births and essentially captures the risk of death in a single pregnancy or a single live birth.

Though the maternal mortality ratio has drastically dropped worldwide over the last six decades WHO in a recent statement mentioned that the 'Maternal deaths declines slowly with vast inequalities worldwide'. Almost 37 in the world have managed to keep the maternal mortality ratio in single digits and the figure 2 shows how these countries are segregated.

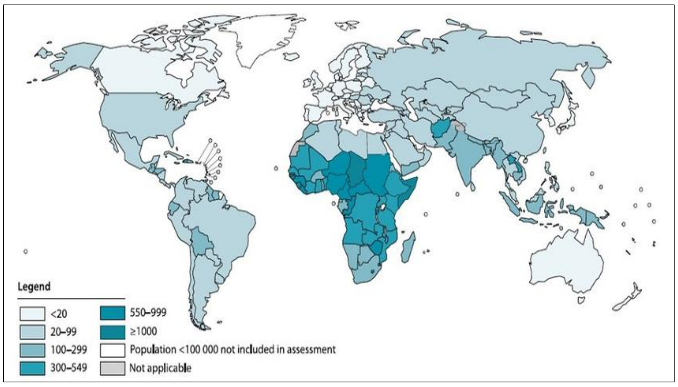

Figure 2: MMR and country profile

As mentioned by the WHO there still exists a drastic variation of maternal mortality ratio between different countries.

The most recent information on maternal mortality statistics by the WHO in 2019 has comprehensively analyzed the data up 2017 and according to their statement:

- Between 2000 and 2017, the maternal mortality ratio dropped by about 38% worldwide.

- Every day in 2017, approximately 810 women died from preventable causes related to pregnancy and childbirth. (one mother dies every 2 minutes)
- 94% of all maternal deaths occur in low and lower middle-income countries.
- Young adolescents (ages 10-14) face a higher risk of complications and death as a result of pregnancy than other women.
- Skilled care before, during and after childbirth can save the lives of women and newborns.

What is the contribution of primary postpartum hemorrhage to maternal mortality?

Primary post-partum haemorrhage, usually defined as a blood loss of more than 500 mL within 24 h of giving birth. It affects about 5% of all women giving birth around the world and is the leading cause of maternal death worldwide, responsible for about 100 000 deaths every year. Most of the deaths occur soon after giving birth and almost all (99%) occur in low-income and middle-income countries. As per 2017 data of the WHO, 810 women who die every day from preventable causes related to pregnancy and childbirth at least 1in 3 or 270 are due to PPH. That is every 5th minute someone somewhere in the world dies of PPH.

Different strategies have been described for preventing postpartum hemorrhage, including active management of the third stage of labour. Once the diagnosis of postpartum hemorrhage is established, the use of uterotonics including prostaglandins, intrauterine balloon tamponades, brace sutures of the uterus and the feeding blood vessel occlusion either surgically or radiologically has been shown to be beneficial. Such strategies save hundreds of mothers from dying due to postpartum hemorrhage every day.

But still majority of women who die around the world due to pregnancy and child birth is caused by postpartum hemorrhage and its complications. Though lack of facilities and substandard care are attributed in low and middle-income countries, in other situations it appeared that we have reached a stalemate with the postpartum hemorrhage and have runout of treatment options. Previously treatment with an antifibrinolytic agent has never been a component of these strategies and it was decided to look at this option after the results of the CRASH 2 trial was published in 2010.

The WOMEN Trial

Again, the Clinical Trials Unit of the London School of Hygiene and Tropical Medicine took up this task which was called the WOMEN trial which stand for 'World Maternal Antifibrinolytic' Trial.

It was a randomized, double-blind, placebo-controlled trial and recruited women aged 16 years and older with a clinical diagnosis of postpartum hemorrhage after a vaginal birth or caesarean section from 193 hospitals in 21 countries. Between March, 2010, and April, 2016.

20 060 women were enrolled and randomly assigned to receive either 1 g intravenous tranexamic acid or a matching placebo in addition to usual care of their PPH.

If bleeding continued after 30 min, or stopped and restarted within 24 h of the first dose, a second dose of 1 g of tranexamic acid or placebo was given.

All analyses were done on an intention-to-treat basis with endpoint of the study being death from post-partum hemorrhage. The results of the most awaited WOMEN trial were published in the Lancet in 2017.

The trial results concluded that:

- Death due to bleeding was significantly reduced in women given tranexamic acid especially in women given treatment within 3 h of giving birth.
- All other causes of death did not differ significantly by group.
- Hysterectomy was not reduced in the tranexamic acid group
- The composite primary endpoint of death from all causes or hysterectomy was not reduced with tranexamic acid
- Adverse events (including thromboembolic events) did not differ significantly in the tranexamic acid versus placebo group.

As a final concluding statement, the WOMEN study collaborative group stated that

'In the WOMAN trial, tranexamic acid was given by intravenous injection. However, in low-income and middle-income countries, many deaths from postpartum bleeding occur at home or settings where intravenous injections might not be feasible. Therefore, bioavailability of tranexamic acid after non-intravenous routes of administration needs to be assessed.'

At the same time in 2017 the WHO in its updated recommendation on tranexamic acid for the treatment of postpartum hemorrhage stated that the use of TXA is only applicable to intravenous administration and the evaluation of potential harm and benefit of **other routs of administration** of TXA is a research priority.

At this point of time there were no published bioavailability studies on tranexamic acid after non-intravenous routes of administration in postpartum women.

Also these statements were made with an optimism that if effective concentration of TXA is achievable by a simpler oral route it could be used in the remotest parts of the world to save women dying from PPH.

Surprisingly at this time a group researcher in Jaffna have already started a study to look at the bioavailability of tranexamic acid after oral administration in postpartum mothers.

The Jaffna Study

The main objective of this study was to evaluate the pharmacokinetics of tranexamic acid after oral administration to postpartum women and the study was started in 2015. In the absence of any published data on the pharmacokinetics of tranexamic acid after oral administration we thought this would be the first step towards considering its oral route of administration to treat PPH or even use it as prophylaxis for PPH.

The study was conducted at the University Obstetric Unit, Teaching Hospital—Jaffna and the plasma drug level measured at the Department of Biochemistry. As per European Medicines Agency Committee recommendation for bioequivalence studies 12 healthy postpartum women with singleton pregnancies were recruited. Recruited participants were screened for contraindications to tranexamic acid: past and current history of intravascular clotting, hemorrhagic events, and procoagulant disorders.

None of the pregnancies had been complicated by pregnancy-related medical disorders, and patients with any preexisting comorbidities were excluded. All participants underwent routine active management of the third stage, with intravenous oxytocin 10 international units after delivery of the neonate, delayed cord clamping, and controlled cord traction to deliver the placenta.

Blood loss was estimated by weighing swabs and blood collected in a waterproof drape on the labor ward. One hour after delivery an arterial line was established by the anesthetist with an aim of obtaining frequent blood samples avoiding repeated venipunctures.

All study participants were administered the same preparation of 2 g of immediate release tranexamic acid orally with 50 mL of water, which corresponds in strength to 1 g of intravenous tranexamic acid used to treat postpartum hemorrhage and they were monitored for 24 hours for adverse effects. After administration of 2g of tranexamic acid orally blood samples were collected over 12 hours namely at t 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 8, 10, and 12 hours each amounting to only 1.8cc. Samples were centrifuged at 2,000g for 15 minutes at room temperature, and supernatants were stored at -70°C until analysis.

One of the biggest difficulties of the analysis was the interference of the HPLC curve of TXA by the amino acid leucine which is present in blood. As a result, each sample had to be pretreated with leucine dehydrogenase before tranexamic acid concentration was determined by HPLC. The accuracy of the assay method was between 97% and 99% and interestingly the standard tranexamic acid used for quality control was obtained from Japan.

The bottom-line of the study was to see whether and effective plasma concentration of tranexamic acid that can significantly inhibit systemic fibrinolysis in postpartum women can be achieved after oral administration. And also, if yes how fast it could be achieved and for how long this concentration lasts.

In one of the most recent systematic review published in the journal Blood Coagulation Fibrinolysis it has been stated that a concentration of between 5–10 micrograms/mL caused significant inhibition and maximal inhibition between 10 and 15 micrograms/mL in adults.

Results of the study.

Demographics of the 12 postpartum women who participated in the study is shown in Table 1 and the figure 3 shows the plasma concentration of tranexamic acid in µg/ml versus time curve following single dose of 2 grams of oral tranexamic acid in individual subjects.

Table 1: Demographics of the 12 postpartum women

Variables	Median	Range
Age (years)	28	24 - 33
Parity	2	1 - 2
Weight (kg) (measured at the onset of labour)	64	59 - 72
Height (cm)	158	150 - 165
BMI (kg/m2)	25.8	24.3 – 28.9
Estimated Blood Loss	230ml	170 - 300
Birth Weight (kg)	3.120	2.730 – 3770

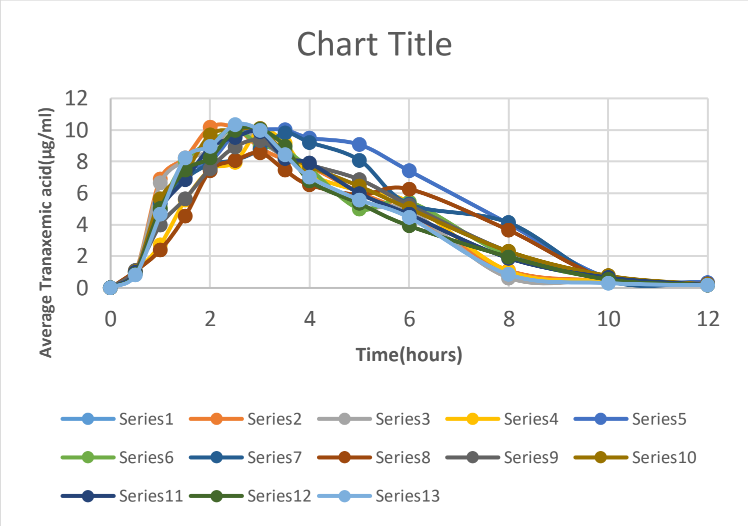

Figure 3: Plasma concentration of tranexamic acid in µg/ml versus time curve following single dose of 2 grams of oral tranexamic acid in individual subjects.

Mean plasma concentration of tranexamic acid in micrograms/mL vs time curve after a single dose of 2 g of oral tranexamic acid in postpartum women with error bars represent the range is displayed in the figure 4 and the table 2 summarizes the pharmacokinetic values

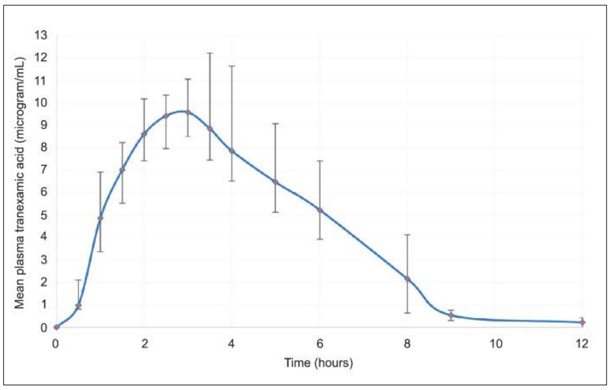

Figure 4: Mean plasma concentration of tranexamic acid in micrograms/mL vs time curve after a single dose of 2 g of oral tranexamic acid in postpartum women. Error bars represent the range.

Table 2: Pharmacokinetic Values

Cmax range	10.06 ± 0.80 µg/dl 8.56 - 12.22 µg/ml
Tmax range	2.92 ± 0.34 hours 2.5 to 3.5 hours
AUC0-12	49.16 µg.h/ml
T1/2	1.65 hours
Time course of concentration ≥5µ/ml Initial Final Duration	 0.87 hours 6.73 hours 5.86 hours

Cmax, maximum observed plasma concentration; Tmax, time to maximum plasma concentration; AUC0–12, area under the curve for drug concentration; T1/2, half-life. The linear trapezoidal method was used to calculate the area under the curve for drug concentration. Geometric means were calculated to estimate the time pharmacologically effective drug concentrations were reached and the duration for which the pharmacologically effective concentrations lasted. Elimination half-life for tranexamic acid was calculated as a parameter describing the linear terminal slope of the log concentrations.

Though there were conflicting results regarding the minimal effective concentration of TXA a recent meta-analysis confirmed that tranexamic acid causes significant inhibition of systemic fibrinolysis in adults at 5–10 micrograms/mL, with near maximal inhibition between 10 and 15 micrograms/mL. At a minimum concentration of 5 micrograms/mL, tranexamic acid has been shown to increase the clot lysis time from 6 to 16 minutes.

Being the first published pharmacokinetic study among postpartum mothers we were able to show that within one hour of oral administration of TXA a minimum effective concentration of 5 micrograms/mL was achievable as stated above. Also, this minimum effective concentration of 5 micrograms/mL lasted for almost 6 hours after a single oral administration.

The peak concentration of 10.06 micrograms/mL (Cmax) was reached by 2.92 hours (Tmax).

Our findings were promising and The Journal of the American College of Obstetricians and Gynecologists accepted to publish our research in January 2020.

Conclusion

Though intravenous TXA has been shown to reduce the MMR due to all causes especially PPH it has to be given intravenously and also within 3 hours of delivery. Looking at the trend in the development of healthcare systems in the world it is unlikely intravenous TXA will be made available these remote locations within foreseeable time frame.

Further the cost of IV TXA worldwide ranges from 3 dollars to 300 dollars and still 80% of the low-income countries do not have access either to IV TXA or lack expertise to deliver it intravenously.

Being able to reach a minimum effective concentration of 5 micrograms/mL within one hour after oral administration, its oral use could be the next possible option available in these situations.

Further with growing evidence of its use intravenous use as prophylaxis for PPH its oral form could be used for the same given its initial promising results.

We foresee a day in future where oral TXA tablets will be a part of the lifesaving menu of birth package in poor and inaccessible regions of the world.

(Lecture based on the publication for which the above medal was awarded)

Publication:

Muhunthan, K., Balakumar, S., Navaratnaraja, T.S., Premakrishna, S. and Arulkumaran, S., 2020. Plasma concentrations of tranexamic acid in postpartum women after oral administration. *Obstetrics & Gynecology*, *135*(4), pp.945-948.

Ecological implications of barrage construction across the Thondamanaru Lagoon, Jaffna Sri Lanka

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Jaffna peninsula

The Jaffna Peninsula, situated at the northernmost part of Sri Lanka, is characterized by flat terrain and lacks natural freshwater sources such as rivers, streams, or waterfalls. As a result, groundwater serves as the main source of water for drinking, household use, and agriculture across the region. However, the quality of groundwater has significantly declined due to several factors. The overuse and mismanagement of aquifers have led to saline intrusion, while fecal contamination and excessive use of agrochemicals have further deteriorated the water quality, making potable water scarce for the local population. The construction of a barrage across the Thondamanaru Lagoon has brought notable ecological impacts. Altering the natural flow and salinity gradients of the lagoon can disturb its delicate estuarine ecosystem, affecting biodiversity, fish migration patterns, and the balance between freshwater and marine environments. These ecological shifts may also have long-term consequences on the livelihoods of people dependent on lagoon fisheries and agriculture.

Thondaimannar lagoon scheme

The initiative to protect the lagoon from seawater intrusion began in 1879, and by 1943, a formal design was introduced to construct a barrage with a sluice gate. The primary aim was to block saline water from entering the lagoon, thereby improving water quality and enhancing irrigation and cultivation in the surrounding areas. The Thondaimannar Barrage, constructed between 1947 and 1953, was part of this effort to transform the lagoon into a freshwater lake (Chitravadivelu, 1993). By 1969, the people of Vadamarachchi were able to use the lagoon water for agriculture, benefiting from a rising groundwater table. Between 1963 and 1973, physical, faunal, and floral changes indicated a gradual reduction in salinity (Chitravadivelu, 1978). However, in 1977, the metal sluice gates corroded and became nonfunctional, leading to seawater seepage. As a result, the barrage system failed and was left in a state of disrepair for many years. Although renovation efforts were undertaken in 2009, the barrages were not operated effectively due to ongoing ethnic tensions and related challenges.

Thondaimanaru lagoon/ Vadamarachchi lagoon

The Thondamanaru Lagoon, located in the northwestern part of the Jaffna Peninsula, is one of the most productive shallow brackish water lagoons in the Northern Province of Sri Lanka. It is hydrologically connected to the Indian Ocean through a narrow channel at Thondamanaru. The lagoon plays a vital role in supporting commercially valuable shellfish and finfish fisheries. Existing structures in Thondamanaru lagoon are Sand bar, Bridge and barrage with sluice gate.

Figures 1-Thondamanaru lagoon, 2-Sand bar, 3-Barrage with sluice gate and 4- Bridge

Prior to the installation of the barrage with sluice gate, the Thondamanaru Lagoon was known for its rich fishery resources and functioned as a highly biodiverse ecosystem, providing employment and livelihoods to the local communities. The lagoon featured both natural and man-made barriers that influenced its hydrology and salinity dynamics. A natural sandbar formed at the mouth of the lagoon, which is seasonally opened and closed by tidal wave action. During the rainy season, the lagoon opens to the sea through an approximately 11m wide mouth, allowing water exchange. In contrast, during dry periods, the sandbar naturally reforms, rising to about one meter above the lagoon water level, thus restricting seawater intrusion and helping to maintain the lagoon's brackish water nature.

To further regulate saltwater inflow and support agricultural development, a man-made barrier (barrage with a sluice gate) was constructed in 1953 by the Irrigation Department. This structure was erected about a quarter mile inland from the lagoon's mouth and spanned across the lagoon, serving to convert the lagoon into a controlled freshwater body for irrigation and ecological management.

The barrage with a sluice gate constructed across the Thondamanaru Lagoon (TL) was primarily designed to function as a saltwater exclusion bund, aimed at preventing seawater intrusion and retaining rainwater within the lagoon. This intervention was intended to convert the brackish lagoon into a freshwater lake, thereby enhancing the water resources of the Jaffna Peninsula (Balendran *et al.,* 2012). The barrage was expected to play a key role in recharging groundwater aquifers and desalinating the adjoining lands, ultimately supporting agriculture and improving potable water availability in the region.

From a broader perspective, barrages serve as vital infrastructure with significant utility for human needs, including, Irrigation support, Water storage and supply, Flood prevention, Hydroelectric power generation, Regulation of water flow and Support of ecosystem functions

However, while the Thondamanaru Barrage has provided socio-economic benefits, its installation has also led to adverse ecological consequences. The alteration of natural hydrological flows disrupted the ecological balance of the lagoon system. This intervention significantly affected the biodiversity of the lagoon, leading to a decline in both faunal and floral species and causing long-term changes to the lagoon's ecosystem structure.

The transformation of a naturally dynamic brackish water body into a controlled freshwater system has challenged the lagoon's unique ecological integrity, highlighting the dual nature of such engineering projects—both as a solution for human development and as a potential threat to sensitive coastal ecosystems.

Effect on lagoon Hydrology

Flow regulation is intricately linked to hydrological changes that can profoundly impact the composition, structure, and function of aquatic ecosystems. By altering key habitat characteristics such as water temperature, oxygen levels, and water chemistry, these changes in water flow can have cascading effects on the ecosystem. Variations in flow dynamics often disrupt the food chain, affecting the entire aquatic life cycle. They can also alter vegetation, particularly mangroves, which are crucial for energy production, habitat provision, food sources, and spawning grounds for various species. Additionally, flow regulation can lead to habitat loss, resulting in a significant decline in biodiversity. Furthermore, the regulation of flow can disrupt fish migration patterns, influencing critical life stages such as spawning, digging behaviors, and migratory movements. These disruptions can negatively affect fish assemblage structure, leading to a decrease in the diversity and abundance of aquatic species in the ecosystem.

Effect on Water Quality

The construction of the barrage across the Thondamanaru Lagoon has led to a significant change in water quality and changes in water parameters, such as: Air and water temperature, Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Salinity and pH levels

These changes have caused a decline in water quality, which directly affects the health of aquatic habitats. For aquatic organisms, self-purification and the improvement of water quality are essential for their conservation and for the ecological restoration of the ecosystem.

Specifically, salinity and temperature affect the health and functiona of the lagoon's ecosystem, as many species cannot tolerate high levels of either, leading to disruptions in their survival and balance within the ecosystem. pH levels also play a crucial role, with aquatic life thriving in neutral to slightly alkaline pH; significant shifts in pH can pose severe threats to aquatic biodiversity. Additionally, turbidity, or a reduction in water transparency, limits photosynthesis, thereby decreasing primary production within the ecosystem. This reduction disrupts vital processes like breeding and feeding, impacting the survival of aquatic organisms. Overall, these changes threat to both the biodiversity and sustainability of the lagoon's ecosystem, affecting the survival of species and the overall ecological balance.

Effect on Aquatic Biodiversity

The construction of a barrage significantly disrupts the natural environment, which is an essential component providing habitat to a wide variety of organisms. The transformation of lotic (flowing) water into lentic (still) water has a negative impact on fish growth and population, affecting their spawning and breeding processes. The alteration of water flow downstream can further disrupt the spawning process by causing the loss of crucial spawning grounds. Additionally, the obstruction of natural water flow affect fish migration, leading to delays and blockages that decrease fish abundance. The feeding patterns of fish are also affected, as the construction destroys phytoplankton and zooplankton communities, which are vital food sources for fish. The fragmentation of the lagoon due to the barrage leads to the destruction of fish habitats and a reduction in fish diversity, habitat destruction, including the loss of mangrove patches and bottom fauna. The absence of mangroves poses a significant threat to faunal diversity, particularly to birds that rely on mangrove flora for nesting and breeding. As a result, the overall aquatic biodiversity is severely affected, with cascading effects on both the ecosystem and the species that depend on it.

Impact of Barrage on Aquatic Biodiversity in Thondamanaru Lagoon

Prior to the installation of the barrage, the lagoon was considered a sanctuary for a wide range of species such as shrimp, crabs, and popular fish species like mullet, rabbit fish, milk fish, and catfish. The lagoon provided an ideal breeding ground for these species, especially white shrimps, which thrived naturally in the lagoon. But construction of the barrage in 1953 has led to significant changes in the Thondamanaru Lagoon's aquatic biodiversity. Fish fauna began to decline, with the number of fish species dropping from 47 in 1968 to just 15 in 1978. Recent studies also show a decrease in fish species, with only 11 species identified in 2014-2015 and just 8 species present in 2018 (Piratheepa et al., 2016).

The construction of the barrage, coupled with the narrowing and eventual closure of the lagoon mouth, disrupted the natural water flow and led to an increase in salinity. These changes, alongside the fragmentation of the lagoon, severely impacted the breeding, migration, and feeding patterns of aquatic life. The obstruction of water flow hindered fish migration, affecting their spawning grounds and causing a reduction in fish abundance. Furthermore, the increased salinity and alteration of the lagoon's ecosystem led to fish deaths, such as the massive fish mortality event observed in 2014, primarily due to high salinity, low oxygen levels, and a lack of water circulation.

Decline in Fisheries and Livelihoods

Before the barrage was built, fish production in Thondamanaru Lagoon was approximately 150 tons per year. However, following the installation of the barrage, fish production drastically decreased to only 35 tons per year by 1978, resulting in the loss of traditional livelihoods for two-thirds of the fishing community. Around 300 fishing families were directly affected, and many fishermen were forced to seek alternative livelihoods.

Similarly, shrimp production in the lagoon has also suffered. Shrimps breed in the sea, and their larvae swim toward the lagoon, where they grow and later migrate back to the sea. The construction of the barrage blocked seawater from entering the lagoon, disrupting the recruitment and breeding of shrimps. As a result, shrimp harvests have drastically declined, with the complete depletion of shrimp stocks observed in recent years. These changes have significantly impacted the livelihoods of the fisherfolk in the region.

Environmental and Ecological Consequences

The installation of the barrage has had dramatic effects on the environment of Thondamanaru Lagoon. Changes in water levels, water movement patterns, and salinity have led to the loss of important flora and fauna. The fragmentation of the lagoon and the alteration of the ecosystem have resulted in the loss of fish nurseries and breeding grounds, affecting migratory fish and bird populations. The destruction of habitat, particularly mangrove patches, has threatened avian life, as many bird species rely on mangrove ecosystems for nesting and breeding.

The lack of water circulation, coupled with high evaporation rates, has caused significant changes in salinity and other water quality parameters. These environmental stresses have led to the loss of species that cannot tolerate the altered conditions, further diminishing the biodiversity of the lagoon.

Research and Development Proposals

Studies on the ecology of Thondamanaru Lagoon have been conducted over the years, with significant contributions from researchers such as Kugathasan (1969) on vegetation and K. Chithravadivelu (1977) on aquatic fauna. The development of the Jaffna Lagoon Scheme by the Irrigation Department began in 1879 and continued until 2018. However, due to the civil war (1978-2014), no further work was carried out on the lagoon's ecosystem. After 2009, the lagoon was considered as part of the regional development agenda, but current records on the lagoon's status remain limited.

In 2014-2015, a baseline study on the development opportunities of Thondamanaru Lagoon was conducted under the Mangrove for Future grant project by the Department of Zoology at the University of Jaffna. The study, led by Prof. T. Eswaramohan and his team, aimed to create a strategic plan for the development of the lagoon, focusing on scientific research and an alternative livelihood plan for the lagoon-dependent communities.

Conclusion

The Thondamanaru Lagoon has undergone significant ecological changes due to the construction of the barrage, which has led to a decline in fish and shellfish diversity, disrupted natural migration patterns, and harmed the livelihoods of the local fishing community. The ongoing environmental stresses, including changes in water quality and habitat loss, continue to threaten the lagoon's ecosystem. Future development plans must focus on restoring the lagoon's ecological balance and supporting sustainable livelihoods for the communities that depend on it.

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Linking Agronomic Resilience to Sustainability in Agriculture

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Introduction

Good afternoon, everyone. It is my pleasure to welcome you to the chairperson address of Section B: Applied Sciences of the Jaffna Science Association, focusing on the topic of linking agronomic resilience to sustainability in agriculture. Unfortunately, I am unable to attend in person as I am currently in the United States for post-doctoral research. Nevertheless, I extend my gratitude to the executive committee and the chairperson of the session for organizing this event and facilitating my virtual participation.

As we face the future of agriculture and food production, it becomes evident that we will encounter numerous challenges. By 2050, the world will need to feed more than 9 billion people. Climate change effects such as increasing temperatures and decreasing precipitation are likely to reduce crop yields, particularly in regions like South Asia and Africa. These changes will also affect livestock production and fisheries. Innovations in agriculture are urgently needed to enhance resilience and sustainability.

Environmental Challenges in Agriculture

Resilience in agriculture is closely linked to sustainability. To understand this connection, we must first identify emerging environmental challenges, such as global warming, soil degradation, deforestation, environmental pollution, and emerging infectious diseases (EIDs). These challenges significantly impact our agricultural and food systems. Global warming, driven by greenhouse gas emissions, leads to temperature increases and more frequent droughts and floods, especially in tropical regions like Sri Lanka. Rising sea levels cause salinity intrusion, reducing valuable agricultural lands. Climate change also affects crop yields and livestock production, altering the dynamics of pests and diseases.

Soil degradation results from continuous agricultural practices, soil erosion, and the overuse of agrochemicals, leading to a loss of soil carbon and nutrients. This degradation impacts crop productivity, making it increasingly difficult to sustain agricultural outputs. Deforestation, driven by the expansion of agricultural lands, contributes to carbon emissions, loss of biodiversity, and disruption of ecosystem services. It also increases the spread of emerging infectious diseases and human-wildlife conflicts. Excessive application of agrochemicals pollutes water, soil, and air, affecting pollinators and human health. Heavy metals in fertilizers further exacerbate these problems. Climate change and anthropogenic activities facilitate the spread of EIDs, affecting plants, animals, and humans. Deforestation and habitat alteration increase contact between pathogens and previously unexposed hosts, leading to new disease outbreaks.

Present Socio-Economic Situation in Sri Lanka

The socio-economic situation in Sri Lanka has been severely affected by the COVID-19 pandemic, followed by a man-made disaster related to the banning of agrochemicals. These events led to negative GDP growth and a high foreign exchange rate, which has stabilized around 300 rupees per dollar. According to the World Food Program's crop and food security assessments in 2022 and 2023, food insecurity remains a significant issue, especially in the northern, eastern, and central provinces. The assessments indicated that in May 2022, approximately 6.4 million people were estimated to be moderately food insecure, with districts such as Kilinochchi, Nuwara Eliya, Mannar, Batticaloa, Vavuniya, and Jaffna experiencing food insecurity rates above 25%.

In May 2023, the situation slightly improved, with 3.9 million people, or 17% of the population, experiencing moderate acute food insecurity. The assessments also highlighted high levels of food insecurity among estate sector workers, particularly those in the tea sector, as well as among Samurdhi and disability beneficiaries, unskilled laborers, fishing communities, female-headed households, and households with low educational engagement. Currently, 36% of households are reducing meal portion sizes, and 19% are skipping meals, underscoring the severity of the situation. Given this context, enhancing agronomic resilience becomes essential for achieving sustainable agricultural outcomes in Sri Lanka. The resilience of agricultural systems must be improved to ensure food security and support the livelihoods of farming communities.

Concept of Resilience in Agriculture

Resilience, initially an engineering concept, can be viewed from various perspectives, including ecological, social, and psychological. For agriculture, ecological resilience is most relevant. Holling (1973) defined ecological resilience as the capacity of a system to recover from stresses, maintaining a level of well-being despite uncertain shocks. Resilience in agriculture involves optimizing productivity, long-term sustainability, and minimizing environmental degradation. It interconnects with social and economic systems, as farmers' livelihoods depend on stable agricultural outcomes. The resilience capacity of an agricultural system can be considered in terms of robustness, adaptability, and transformability.

Robustness is the ability of an agricultural system to withstand anticipated or unanticipated shocks, such as climate events. Adaptability refers to the capacity to change inputs, production, and risk management in response to shocks without altering the system's structure. Transformability is the ability to significantly change the internal structure and feedback mechanisms of the agricultural system in response to severe shocks or enduring stress.

Internally regulated agro-ecosystems, which rely on natural processes like nitrogen and carbon cycling, water conservation, and pest suppression, can maintain productivity within a range even during disturbances. Externally regulated systems, dependent on external resources like fertilizers and pesticides, are more vulnerable to disturbances, pushing productivity into unproductive areas. Therefore, promoting natural and regenerative farming can enhance resilience and sustainability.

Agronomic resilience is the ability of agricultural systems to maintain their structures and behaviors in the face of climate and other perturbations, continuing to provide ecosystem services and desirable outputs like production and profit. Agronomic approaches, such as planting with the onset of rains, using organic fertilizers, and adopting short-duration crop varieties, can enhance resilience. Long-term research from the US Department of Agriculture shows that no-till and mixed crop systems improve soil organic matter and resilience.

Agronomic Approaches to Enhance Resilience with Research Examples

Increasing structural and genetic diversity through crop rotation, polyculture, agroforestry, and mixed landscapes can buffer against shocks, ensuring that not all components are affected simultaneously. Considering the interconnectedness of energy, water, and food, resilience can be enhanced by addressing risk drivers like environmental changes, economic factors, and governance. For example, in the United States, long-term agricultural experiments have demonstrated that no-till and mixed perennial-annual systems improve soil organic matter, particularly in the top 0-10 cm of soil. This is crucial for soil health, as soil organic carbon helps store water, promote biotic organisms, and provide other benefits. These practices also reduce soil erosion, further enhancing resilience.

I am now exploring a system thinking approach to resilience, considering the interconnectedness of energy, water, and food. This energy-water-food (EWF) nexus highlights the importance of addressing risk drivers across these interconnected systems. By understanding the broader picture, we can develop strategies to enhance resilience and sustainability in agriculture.

Measuring Resilience

To assess resilience, it is essential to ask specific questions: Resilience of what? (e.g., farming systems), Resilience to what? (e.g., climate change), Resilience for what purpose? (e.g., maintaining production), What resilience capacity? (e.g., robustness, adaptability, transformability), and What enhances resilience? (e.g., specific practices or interventions). Resilience can be quantified using metrics like agricultural production, crop yield, farm revenue, food security, and ecosystem services.

In addition to traditional metrics, resilience can also be evaluated in terms of ecosystem services. For example, in one of my research projects, I assessed resilience by examining groundwater recharge. By comparing conventional and no-till systems, I found that no-till practices improved groundwater recharge, benefiting wetlands and supporting biodiversity.

Resilience in agriculture is not a static concept; it evolves with changing environmental and socio-economic conditions. Therefore, continuous monitoring and assessment are necessary to understand the dynamic nature of resilience. By integrating data from various sources, such as satellite imagery, climate models, and field observations, we can develop comprehensive resilience assessment frameworks.

Agronomic Resilience and Sustainability

Sustainability in agriculture is supported by three pillars: social, economic, and environmental components. Agronomic resilience is crucial for achieving sustainability, as it integrates these components holistically. To improve resilience in agriculture, we need system thinking, collaborative research and dissemination, improved methodologies to assess resilience, and decision support systems for agricultural stakeholders. Digital agriculture, leveraging AI and the Internet of Things (IoT), can support precision resource management. System research and dissemination are essential because agricultural challenges are interdisciplinary and vary across different disciplines. Collaborative research involving natural scientists, social scientists, community stakeholders, and statisticians can provide comprehensive solutions to improve agronomic resilience.

Assessing resilience across the entire production and supply chain, from raw material extraction to farming and harvesting, is crucial. Decision support systems, utilizing data from satellite images, drones, and sensors, can help farmers take precautionary actions, ultimately improving agricultural resilience. Digital agriculture, with AI and precision resource management, can make challenges more manageable, especially those related to climate change and soil health.

Resilience is key to achieving sustainability in agriculture. Resilience and sustainability are closely linked, particularly in the face of increasing environmental changes. By building resilient systems, we can ensure sustainable agricultural practices and secure food production for future generations.

Way Forward and Recommendations

Moving forward, several key actions can enhance agronomic resilience and sustainability in agriculture. First, fostering system thinking and interdisciplinary collaboration is essential. Integrating knowledge from various disciplines, such as natural sciences, social sciences, and economics, can help develop comprehensive solutions to address agricultural challenges. Engaging community stakeholders, including farmers, agricultural extension services, and non-governmental organizations, is also crucial for successful implementation.

Second, improving methodologies to assess resilience is vital. Developing robust frameworks and indicators to measure resilience across different agricultural systems can provide valuable insights into areas requiring intervention. This can help policymakers and practitioners make informed decisions to enhance resilience.

Third, promoting digital agriculture and precision resource management can significantly improve resilience. Leveraging AI, IoT, and other advanced technologies can optimize resource use, monitor environmental conditions, and provide real-time data for decision-making. Ensuring that these technologies are accessible to farmers, particularly in developing regions, can help them adapt to changing conditions and improve productivity.

Fourth, investing in capacity building and education is essential for enhancing resilience. Training programs for farmers and agricultural professionals can provide them with the knowledge and skills needed to adopt resilient practices. Additionally, promoting awareness of the importance of resilience and sustainability can encourage broader adoption of these concepts.

Finally, supporting policy frameworks that promote resilience and sustainability is critical. Governments and international organizations can play a significant role in creating an enabling environment for resilient agricultural practices. This includes providing financial incentives, supporting research and innovation, and implementing regulations that protect natural resources and promote sustainable farming practices.

Parenting is an Art as well as a Science

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Khalil Gibran said "Your children are not your children. They are the sons and daughters of Life's longing for itself. They come through you but not from you, and though they are with you yet they belong not to you".

Parenting is one of the most profound roles a human being can undertake. It is both a privilege and a responsibility. At its core, parenting involves guiding, nurturing, and shaping a young life a task that demands both emotional intelligence and informed decision-making. That is why parenting is not merely a natural instinct; it is both **an art and a science**.

Good parenting starts not after the birth of a child. It starts when parents plan to become parents and even before that.

A person's first 1,000 days, or the period from conception to age two, are the most crucial for the development of their body, brain, metabolism, and immune system.

A baby's experiences in their first 1,000 days can have a life-long effect on their health and wellbeing. Stress, trauma, poverty and violence experienced during the first 1000 days can have long term negative health effects on your baby.

It is important to provide your baby with good nutrition, safety and security and a loving home environment, especially during their first 1000 days.

The Science of Parenting

Parenting as a science draws from research in child development, psychology, neuroscience, and education. Scientific parenting involves understanding how children grow physically, emotionally, and cognitively at various stages. It includes:

- **Applying evidence-based strategies**: Such as positive reinforcement, setting appropriate boundaries, and using age-appropriate communication.
- **Understanding brain development**: Knowing how a child's brain matures helps in setting realistic expectations and providing the right stimulation.
- **Health and nutrition**: Ensuring proper diet, sleep, and healthcare are foundational aspects supported by science.

- **Behavioral psychology**: Using knowledge of learning theory and behavior management to correct or encourage certain behaviors.

Parents today have access to a vast amount of information backed by decades of research. But while science gives a framework, it does not account for every unique personality or situation.

The Art of Parenting

The art of parenting lies in the heart — the intuition, empathy, and creativity that come into play in everyday situations. Every child is different, and what works for one may not work for another. Artistic parenting involves:

- **Emotional connection**: Understanding your child's unspoken needs, comforting them, and being their emotional anchor.
- **Adapting creatively**: Finding new ways to explain concepts, handle tantrums, or inspire discipline through storytelling, play, or shared experiences.
- **Balancing roles**: Knowing when to be a teacher, when to be a friend, and when to just listen without judgment.
- **Instilling values**: This is not taught through textbooks but through modeling behavior, shared traditions, and moral storytelling.

Art comes from experience, reflection, and often, trial and error. It's about being present, flexible, and human.

The Harmony Between the Two

The best parenting happens when science informs the mind and art guides the heart. A parent who knows developmental milestones (science) but also knows how to soothe a crying child at midnight with a gentle lullaby (art) is blending both beautifully.

For example, knowing that toddlers throw tantrums due to limited emotional regulation (science) is important. But calming them with a story or a warm hug (art) is what truly nurtures the bond.

Parenting your child in smart and healthy way

1. Listen them before advising
2. Praise the positives
3. Set clear expectations
4. Allow them to speak
5. Ask questions.

6. Validate their emotions & feelings.
7. Teach them "wants & needs".
8. Don't compel them. Convince them.
9. Don't live through your child
10. Surround them with good people.
11. Teach them to say "No".
12. Ask their opinion
13. Respect them
14. Make good attitude about money. – Saving habit

Conclusion

Parenting is a lifelong journey of learning, loving, and evolving. It demands both knowledge and intuition, structure and spontaneity, logic and love. When science and art go hand in hand, parents can raise not just well-behaved children, but confident, compassionate, and resilient human beings. In a world that constantly changes, the science of parenting gives us tools — but the art of parenting gives it soul.

விஞ்ஞான வளர்ச்சியில் தோமஸ் கூனின் கட்டளைப்படிம மாற்றம் பற்றிய முறையியற் சிந்தனையும் அவற்றின் பிரயோகத்தன்மைகளும்

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கலைப்பீடம்,
யாழ்ப்பாணப் பல்கலைக்கழகம், இலங்கை

அறிமுகம்

இருபதாம் நூற்றாண்டில் தோற்றம்பெற்ற முறையியற் சிந்தனையாளர்களுள் தோமஸ் கூன் குறிப்பிடத்தக்க ஒருவராவார். விஞ்ஞானத்தை வரலாற்று ரீதியாக ஆராய்ந்து, அதன் அறிவு வளர்ச்சி மற்றும் அதனூடான புரட்சி பற்றித் தெளிவுபடுத்திக் கட்டளைப்படிம மாற்றம் பற்றிய முறையியற் சிந்தனையை வெளிக்கொணர்ந்தார். குறிப்பாக, கூனின் கட்டளைப்படிம மாற்றம் (Paradigm Shift) பற்றிய முறையியற் சிந்தனை விஞ்ஞான வளர்ச்சியில் புரட்சிகரமான மாற்றத்தினை ஏற்படுத்தியிருந்தன.

கூன், விஞ்ஞான வரலாறு தொடர்பாக நிகழ்த்திய ஆய்வுகளில் சார்புவாதச் சிந்தனையை விருத்திசெய்து அதிலிருந்து கட்டளைப்படிம மாற்றம் பற்றிய முறையியற் சிந்தனையை வெளிக்கொணர்ந்தார். இம்முறையியல் மூலம் இதுவரை காலமும் விஞ்ஞான வரலாற்றில் நிலவி வந்த ''மாறாத உண்மை'' என்ற கருத்தாக்கம் நிராகரிக்கப்பட்டது. வரலாற்று நோக்கில் ஒருமைவாதம் எவ்வாறு பின்னவீனத்துவத்தின் மையக்கருத்தான பன்மைவாதத்திற்கு இட்டுச் சென்றது என்பதைக் கூனின் விஞ்ஞான வரலாறு மற்றும் அறிவு வளர்ச்சி தொடர்பான ஆய்வுகளிலிருந்து விளங்கிக்கொள்ளலாம்.

கூனினுடைய நோக்கில், விஞ்ஞானத்தில் புதிதாக வெளிக்கொணரப்படும் உண்மையானது (கொள்கை அல்லது விதி) மாற்றமடையும் போக்கினைக் கொண்டதாகும். இக்கருத்தியலின் பின்னணியிலேயே கூன், கட்டளைப்படிம மாற்றம் பற்றிய முறையியற் சிந்தனையை விளக்குகின்றார். இம்முறையியல் புரட்சிகரமான மாற்றத்தினை ஏற்படுத்தியதோடு புத்தாக்க சிந்தனையையும் உருவாக்கியிருந்தது.

கூனினுடைய முறையியற் சிந்தனை பின்வரும் இரண்டு வினாக்களை அடிப்படையாகக்கொண்டு விளங்குகின்றன;

1. விஞ்ஞானக் கொள்கைகள் ஏன் ஏற்றுக்கொள்ளப்படுகின்றன?
2. ஏன் விஞ்ஞானக் கொள்கைகள் மாற்றீடு செய்யப்படுகின்றன?

விஞ்ஞானம் தர்க்கபூர்வமான முடிவுகளையும், விளக்கங்களையும் கண்டடைவதை நோக்கமாகக்கொண்டு இயங்குகிறது. இதன்மூலம் புதிய உண்மைகள், கொள்கைகள் வெளிக்கொணரப்பட்டு விஞ்ஞானிகள் சமூகத்தினால் ஏற்றுக்கொள்ளப்படுகின்றன. இவ்வாறு ஏற்றுக்கொள்ளப்பட்ட கொள்கைகள் காலப்போக்கில் தொடர்ச்சியாக மேற்கொள்ளப்படும் ஆய்வுகள் மூலம் வலுவிழந்து செல்ல, புதிய கொள்கைகள் தோற்றம்பெறுகின்றன. இதனால் விஞ்ஞானம் வளர்ச்சியடைந்து செல்வதோடு அறிவும் கட்டமைக்கப்பட்டு வருகின்றன. இத்தகைய செல்நெறிப்போக்கினை அடிப்படையாகக்கொண்டே கூன் தமது முறையியற் சிந்தனையைத் தெளிவுபடுத்தி விருத்திசெய்தார்.

கட்டளைப்படிமம்

அறிவின் வளர்ச்சி பற்றிப் பொதுவாகவும் விஞ்ஞான அறிவின் வளர்ச்சி பற்றிக் குறிப்பாகவும் ஆராய்ந்த கூன், தமது ஆய்விற்குரிய பொருளாக இயற்கை விஞ்ஞானத்தின் வரலாற்றை எடுத்துக்கொண்டு அது தொடர்பான ஆய்விலிருந்து அறிவின் வளர்ச்சி பற்றிய பொதுத் தத்துவம் ஒன்றையும் உருவாக்கினார். அதனையே அவர் கட்டளைப்படிமம் (Paradigm) என அடையாளப்படுத்தினார். கூனின் இம்முறையியற் சிந்தனையை சமகால முறையியற் சிந்தனையாளரான போல் பெயராபெண்ட் "உயர்நிலைக் கோட்பாடு" (High Level Theory) என்ற பெயரில் அறிமுகப்படுத்தினார். இவ்வுயர்நிலைக் கோட்பாடு அல்லது கட்டளைப்படிமம் முழு விஞ்ஞானத் துறையினையும் உள்ளடக்கியதொன்றாக விளங்குகிறது எனலாம்.

கட்டளைப்படிமம் குறித்துப் பல்வேறுபட்ட வரைவிலக்கணங்கள் முன்வைக்கப்பட்டிருக்கின்றன. இருந்தும் இரண்டு விளக்கங்கள் முதன்மையானதாகக் காணப்படுகின்றன. ஒன்று, முறையியல் வரலாற்றில் விஞ்ஞானிகள் சமூகம் ஏற்றுக்கொண்ட பொது உடன்பாட்டை கட்டளைப்படிமம் எனக் கூன் அழைக்கிறார். அதாவது விஞ்ஞானிகள் சமூகத்தினால் ஏற்றுக்கொள்ளப்பட்ட பொதுவான நம்பிக்கைகள், விழுமியங்கள், உத்தி முறைகள் ஆகியவற்றின் முழுமையான மொத்த வடிவமே கட்டளைப்படிமம் என்பதாகும். இதனையே கூன் மாதிரி (Model), பிரதி (Pattern) என்றழைக்கின்றார். இரண்டாவதாக, கட்டளைப்படிமம் ஒன்றானது தனிப்பட்ட மூலக்கூறாகக் கருதமுடியாது. அவை பல விடயங்கள் ஒன்றிணைந்த முழு மொத்த வடிவமாகவும் விளங்குகின்றது. அதாவது நியூட்டனுடைய விதிகள் இதற்குச் சிறந்த எடுத்துக்காட்டாகும்.

விஞ்ஞான ஆராய்ச்சியின்போது வெளிக்கொணரப்படும் பொது உண்மையான கட்டளைப்படிமத்தினைக் கருத்தியலாக விஞ்ஞானத்திற்கு வழங்க வேண்டும் என்பதே கூனின் முறையியற் சிந்தனையின் நோக்கமாகும். அதுவரை காலமும் விஞ்ஞான அறிவு வளர்ச்சி என்பது ஒரு சிலரால் கலை எனக் கருதப்பட்டு வந்திருந்தபோதிலும் அச்சிந்தனையை இயற்கைவியலின் பாற்பட்ட ஒரு விஞ்ஞான முறையியலாக நிரூபித்தவர் இவரேயாவார். விஞ்ஞான முறையியல் வளர்ச்சியில் நியூட்டனுடைய ஈர்ப்புக் கோட்பாடு, ஐன்ஸ்ரைனுடைய சார்புக் கோட்பாடு, டால்ரனுடைய அணுக் கோட்பாடு, கொப்பனிக்கஸினுடைய சூரியமையக் கோட்பாடு போன்றன யாவும் கட்டளைப்படிமங்களுக்குச் சிறந்த எடுத்துக்காட்டுக்களாக விளங்குகின்றன எனக் குறிப்பிட்டார்.

கூனினுடைய நோக்கில் கட்டளைப்படிமம் என்பது விஞ்ஞான வரலாற்றில் தொடர்ச்சியாக ஏற்றுக்கொள்ளப்படுவதில்லை. மனிதனுடைய சிந்தனை ஆற்றலும் இடையறாத தேடலின் மூலமும் விஞ்ஞான அறிவுத்துறை வளர்ச்சியடைந்து செல்வதோடு புதிய மாற்றங்களையும் கண்டு வருகின்றது. இதனடிப்படையிலேயே விஞ்ஞானத்தில் ஒருபொழுதும் மாற்றமடையாத அல்லது நிராகரிக்கப்படாத கட்டளைப்படிமம் என ஒன்றிருக்கமுடியாது என நிறுவியிருந்தார். இதன் மூலம் விஞ்ஞானத்திற்கு புதிய மாற்றத்தினை வெளிக்கொணர்வதனையே நோக்கமாகக் கொண்டிருந்தார்.

எனவேதான், விஞ்ஞான வரலாற்று வளர்ச்சியில் பொது உண்மையான கட்டளைப்படிமம் ஒன்று நிலைநிறுத்தப்பட்டாலும் தொடர்ச்சியாக மேற்கொள்ளப்படும் ஆய்வுகளின் மூலம் அப்படிமம் மாற்றமடைந்து செல்லும் என்பதே வரலாற்றிலிருந்து அறிந்துகொள்ளும் உண்மையாகும். கட்டளைப்படிமம் பற்றிய சிந்தனையை ஆய்விற்குட்படுத்திய முறையியற் சிந்தனையாளரான லக்கடோஸ், கட்டளைப்படிமம் என்பதற்குப் பதிலாக திடமான ஒரு கருத்தினை மையமாகக் கொண்ட

"ஆய்வு நிகழ்ச்சித் திட்டம்" (Research Program) எனக் குறிப்பிடுவது பொருத்தமானது என விளக்கியிருந்தார்.

விஞ்ஞான வரலாறு மற்றும் அறிவு வளர்ச்சி பற்றிய கூனின் நோக்கு

மனிதன் ஆரம்பம் முதல் தன்னைச் சூழ்ந்துள்ள உலகு, அதிலுள்ள பொருட்களைப் பற்றி அறிந்துகொள்ள முயன்று வந்திருக்கின்றான். விஞ்ஞானத்தின் முன்னேற்றம் அதனூடான வளர்ச்சி பற்றிப் பேட்டன் ரஸல் கூறுகையில், "எங்கோ இருக்கும் நட்சத்திரங்கள் மற்றும் கிரகணங்கள் தொடர்பாக ஆராயும் பணியில் விஞ்ஞான முயற்சிகள் ஆரம்பிக்கப்பட்டன. நியூட்டன் காலம் வரை அப்படியே நடந்தது. அடுத்தபடியாக நமக்கு நெருங்கிய மனித உடலைப் பற்றி 19ஆம் நூற்றாண்டில்தான் விஞ்ஞான ஆராய்ச்சிகள் தீவிரமாகத் வளர்ச்சியடையத் தொடங்கியது".

இவ்வாறு, படிப்படியாக வளர்ச்சியடைந்த விஞ்ஞான அறிவு பல துறைகளையும் உள்வாங்கிக் கொண்டு விரிவுபெற்றது. குறிப்பாக நியூட்டன், ஐன்ஸ்ரைன் (கி.பி. 1879-1955) போன்றோர்களது சிந்தனைகளைக் குறிப்பிடலாம். வில்லியம் தோம்ஸன் (கி.பி. 1824-1907) என்பவர் நியூட்டனுடைய சிந்தனைகளை வெப்பவியலுக்கு விரிவுபடுத்தி ஆய்வுகளை மேற்கொண்டார். தொடர்ந்து ஆய்வுகள் மூலம் வெளிக்கொணரப்பட்ட சிந்தனைகளில் மாற்றங்கள் உருவாகி எந்தவொரு கோட்பாடும் சரியான சோதனைச் சான்றுகளுடன் ஐயத்திற்கு இடமின்றி நிரூபிக்கப்பட வேண்டும் என்ற சிந்தனை இக்காலப்பகுதியில் முன்மொழியப்பட்டது.

விஞ்ஞானம், அதன் வளர்ச்சி பற்றி வரலாற்று ரீதியாகப் பல சிந்தனையாளர்கள் ஆராய்ந்து புதிய பல உண்மைகளை வெளிக்கொணர்ந்தனர். இப்பின்னணியிலேதான் கூனினுடைய சிந்தனை முதன்மை பெறுகின்றது. விஞ்ஞான வரலாற்றின் ஊடாக அறிவு வளர்ச்சி பற்றி ஆராய முற்பட்ட கூன் அவ்வளர்ச்சியை இருவேறு காலகட்டங்களாகப் பிரித்து நோக்குகின்றார். அவைமுறையே,

1. விஞ்ஞானிகளின் சமூக உருவாக்கத்திற்கு முற்பட்ட காலம்
2. விஞ்ஞானிகளின் சமூக உருவாக்கத்திற்குப் பிற்பட்ட காலம்

விஞ்ஞானிகளின் சமூக உருவாக்கத்திற்கு முற்பட்ட காலத்தில் இயற்கை, அதன் தோற்றப்பாடுகள் பற்றி ஒன்றுக்கொன்று முரண்பட்ட கொள்கைகள் காணப்பட்டன. இக்காலத்தில் விஞ்ஞானத்தின் நோக்கம், அதன் முறைகள் பற்றியும் மாறுபட்ட அபிப்பிராயங்களைக் கொண்டவர்களாக விஞ்ஞானிகள் காணப்பட்டனர். ஒன்றுக்கொன்று ஒத்திசையாத உலக நோக்கினைக் கொண்டிருந்ததால் அவர்களிடையே பொதுவான உடன்பாடு காணமுடியவில்லை.

எடுத்துக்காட்டாக, ஆரம்ப காலத்தில் குறிப்பாக, ஆதி கிரேக்ககால சிந்தனையில் அனைத்திற்கும் அடிப்படையாக விளங்குவது எது? என்ற வினாவிற்கான தேடலே முதன்மை பெற்றிருந்தது. இத்தேடலில் ஈடுபட்ட சிந்தனையாளர்கள் ஏற்புடைய முடிவினைப் பெற்றுக்கொள்வதில் முனைப்புடன் செயற்பட்டனர். இதன் விளைவாகவே தேலீஸ் அனைத்திற்கும் அடிப்படை நீர் என்றும் அனெக்ஸிமாந்தர் எல்லையற்றது என்றும் அனெக்ஸிமினிஸ் காற்று என வெவ்வேறுபட்ட முடிவுகளை வெளிக்கொணர்ந்தனர். இவ்வாறு ஆராய்ச்சியின்போது வெளிக்கொணரப்பட்ட முடிவுகளைத் தொடர்ந்து விஞ்ஞானிகள் சமூகம் தோற்றம்பெற்றிருந்தது. இதுவே இரண்டாவது காலகட்டமாகும்.

விஞ்ஞானிகள் சமூகம் தோற்றம் பெற்றதனையடுத்து அவர்கள் ஒருங்கிணைந்து செயற்பட்டுப் பல ஆராய்ச்சிகளை மேற்கொள்ளுகின்றனர். இதன் விளைவாக வெவ்வேறுபட்ட உண்மைகள்

வெளிக்கொணரப்பட்டன. விஞ்ஞானிகளால் ஏற்றுக்கொள்ளப்பட்ட பொதுவான உண்மைகள், நம்பிக்கைகள், விழுமியங்கள், உத்தி முறைகள் ஆகியவற்றின் முழுமையான மொத்த வடிவமே கட்டளைப்படிமமெென அழைக்கப்படுகிறது. விஞ்ஞானிகளிடையே காணப்படும் மேற்குறித்த பொது உடன்பாடு அவர்களை ஒரு சமூகமாக இயங்கவைக்கிறது என்பது கூனின் அபிப்பிராயமாகும்.

சாதாரணகாலம், புரட்சிக்காலம்

விஞ்ஞானத்தின் வரலாற்று ரீதியான வளர்ச்சியை ஆராய்ந்த போது அவ்வளர்ச்சியிலும் சாதாரண காலம் (Normal Period), புரட்சிக் காலம் (Revolution Period) என இரு வெவ்வேறுபட்ட கூறுகள் உள்ளடங்கி இருப்பதாக கூன் விளக்கினார். சாதாரண காலத்தில் விஞ்ஞானம் கிடைவெட்டாக வளர்ச்சியடைகின்றது என்றும் இக்காலத்தில் விஞ்ஞான ரீதியாக மேற்கொள்ளப்படும் ஆராய்ச்சிகளைக் கட்டளைப்படிமமே வழிநடாத்துகிறது என்பது கூனின் முறையியற் சிந்தனையாகும்.

விஞ்ஞானத்தில் மறுமலர்ச்சியுடன், குறிப்பாக 16ஆம் நூற்றாண்டுகளில் புரட்சிகள் அதிகளவு இடம்பெற்றிருந்தது. பல நூற்றாண்டு காலமாக சமய ரீதியான சிந்தனையில் மூழ்கியிருந்த மக்கள் அதிலிருந்து விடுபட்டு எங்கும், எதிலும் புதுமை காண விழைந்தனர். இந்நிலைப்பாடே பல துறைகளிலும் புரட்சிகள் தோன்ற அடிப்படையாயிற்று. விஞ்ஞானத்தில் புரட்சியினால் புதிய வடிவங்களுக்குள்ளாகிய துறைகள் மேலும் வளர்ச்சி பெற்று, மாற்றங்கள் கண்டு விளங்கியதோடு ஏற்கனவே ஏற்றுக்கொள்ளப்பட்ட கொள்கைகளும், விதிகளும் கூட மாற்றங்களுக்குள்ளாகின. அத்தோடு வரலாற்றில் புரட்சியின் விளைவாக கட்டளைப்படிமங்களில் பல மாற்றங்கள் நிகழ்ந்துள்ளன.

கூனின் கருத்துப்படி ஒரு கட்டளைப்படிமத்திலிருந்து பிறிதொரு கட்டளைப்படிமத்திற்கு மாறுவதென்பது, ஒரு நீண்ட செயன்முறைக்கூடாகவே நிகழ்கிறது. அதாவது விஞ்ஞானிகள் சமூகத்தால் தொடர்ச்சியாக மேற்கொள்ளப்படும் ஆய்வுகளின் மூலம் ஒவ்வொரு காலகட்டத்திலும் வெவ்வேறுபட்ட கட்டளைப்படிமங்கள் தோற்றம்பெறுகின்றன. இவை பல நிலைகளைத் தாண்டியே எழுச்சி பெறுகின்றது. இதனை கூன் பின்வருமாறு விளக்கிக்காட்டினர்.

கட்டளைப்படிமம் → சாதாரண காலம் → அசாதாரண தோற்றப்பாடுகள் → நெருக்கடி → புரட்சி → புதிய கட்டளைப்படிமம்

கட்டளைப்படிமம் ஒன்றிலிருந்து பிறிதொன்றிற்கு மாறுவதைப் புரட்சிக் காலம் என்றும் இரண்டு கட்டளைப்படிமங்களிற்கு இடைப்பட்ட காலத்தைச் சாதாரண காலம் என்றும் கூன் வரையறை செய்கின்றார். இச்சாதாரண காலத்தில் வழிநடத்திச் செல்லும் கட்டளைப்படிமத்தில் ஏற்படும் அசாதாரண தோற்றப்பாடுகள், நெருக்கடிகளின் பேறாக மாற்றீடாக முன்மொழியப்படும் புதிய கட்டளைப்படிமமானது புரட்சிகரமான மாற்றத்தை ஏற்படுத்துகின்றதோடு இத்தகைய புரட்சியானது சாதாரண கால விஞ்ஞானங்களிலிருந்து சடுதியாகத் தோற்றம்பெற்றதொன்றல்ல. அதாவது, சாதாரண காலத்தில் விஞ்ஞான ஆய்வினை வழிநடத்திச் செல்லும் கட்டளைப்படிமமானது பல்வகைப்பட்ட நிலைகளைத் தாண்டியே புரட்சிகரமான சிந்தனையைத் தூண்டுவிக்கின்ற விஞ்ஞானமாக மாற்றமடைகின்றது. இப்புரட்சியின்போதே புதிய கட்டளைப்படிமம் தோற்றம் பெறுகிறது என்பது கூனின் முறையியற் சிந்தனையாகும்.

விஞ்ஞான வரலாற்றில் சாதாரண கால விஞ்ஞான ஆய்வானது மேலதிகமான விதிகளை வெளிக்கொணர்வதோடு விஞ்ஞானிகள் கட்டளைப்படிமங்கள் தொடர்பாகச் செய்யும் சிபார்சுகளையும் உள்ளடக்கியதாகக் காணப்படும் என்பதால் அவை அதிக நம்பகத் தன்மையுடையதும் வெளிப்படையானதுமான விளக்கங்களையும் கொண்டிருக்கும்.

சாதாரண காலத்தில் விஞ்ஞானிகள் கோட்பாடுகளைச் சோதிப்பதோ அல்லது ஆராய்வதோ அல்ல. கட்டளைப்படிமத்திற்கும் பரிசோதனைக்குமிடையே உடன்பாடான முடிவுகள் கிடைக்கப் பெறுவதையே அக்கால விஞ்ஞானிகள் இலக்காகக்கொண்டு செயற்படுகின்றனர். எனவேதான் எல்லா விஞ்ஞானிகளது ஆய்வுச் செயற்பாடுகள் இக்கால கட்டத்தில் ஒரே கட்டளைப்படிமத்தை அடியொற்றியதாகக் காணப்படுகின்றது. இதனால் இக்கால விஞ்ஞானங்களில் புதிர்களை விடுவிக்கும் செயற்பாடே நடைபெறுகின்றன.

விஞ்ஞானிகள் சமூகமானது சாதாரண காலத்தில் தமது ஆய்வுத் துறையில் நிகழும் பிரச்சினைகளை ஆய்விற்கு வழிகாட்டும் கட்டளைப்படிமத்தை ஆதாரமாகக்கொண்டு வரையறுத்துக்கொள்வார். அத்தோடு குறிப்பிட்ட பிரச்சினைக்குரிய தீர்வையும் கண்டுபிடிக்க முயல்வர். இக்கால விஞ்ஞானிகள் தமது கட்டளைப்படிமத்தின் எல்லைகளிற்குட்படாத பிரச்சினைகளைப் பௌதிகவதீதப் பிரச்சினைகளாகக் கருதி அவற்றை நிராகரிக்க முயல்கின்றனர்.

விஞ்ஞான அறிவின் வளர்ச்சிப்போக்கில் புதிய கட்டளைப்படிமங்கள் தொடர்ச்சியாக மாற்றங்களிற்குட்படுவது வழக்கமாகும். அதாவது, ஆய்விற்கு வழிகாட்டுகின்ற கட்டளைப்படிமமானது அதன் ஆரம்ப கட்டத்தில் மிகக் குறைந்த அளவிலான நெருக்கடிகளைக் கொண்டிருப்பது இயல்பானதாகும். பின்னர் அவை தொடர்பாக மேற்கொள்ளப்படும் பரிசோதனைகளின் போதே அதனுடைய நெருக்கடிகள் பூரணமாக அவதானிக்கப்படும். விஞ்ஞான வரலாற்றில் முன்மொழியப்படும் கட்டளைப்படிமங்கள் சாதாரண ஆய்வுகளை வழிநடத்திச் செல்வதற்கு அவசியமானவை. எனினும் அவை நெருக்கடிகளுக்கு ஊடாகப் புரட்சியினை ஏற்படுத்தத் தூண்டுவிக்கின்றன.

விஞ்ஞானத்தில் புரட்சியின் மூலம் கட்டளைப்படிமங்கள் மாற்றம் பெறுகின்றபோது புதிய கட்டளைப்படிமமானது உலக நோக்கை மாற்றுகின்றது. உதாரணமாக, எரிதலுக்குக் காரணம் புளொஜிஸ்தோன் எனும் பதார்த்தமல்ல ஒட்சிசன் வாயுவே என நிரூபிக்கப்பட்டதைத் தொடர்ந்து உலகநோக்கு முற்றிலும் மாற்றமடைந்து, புதிய உண்மையையும் பெற்றுக்கொண்டது. விஞ்ஞானத்தில் ஏற்படுகின்ற புரட்சிகளே புதிய கட்டளைப்படிமங்களை உருவாக்குகின்றது. அவ்வாறு உருவாக்கப்படும் கட்டளைப்படிமமானது உறுதியானதாகவும் துறை தொடர்பான விளங்கங்களை உள்ளடக்கியதாகவும் ஆய்வு விடயம் தொடர்பாக வினாவப்படும் அனைத்து வினாக்களுக்கும் விடையளிக்கக் கூடியதாகவும் இருத்தல் வேண்டும். அவ்வாறில்லையேல் புதிய கட்டளைப்படிமம் என்ற அந்தஸ்தத்தினை இழக்க நேரிடும்.

விஞ்ஞானத்தில் புரட்சியினூடாக அறிவில் பரிணாம வளர்ச்சி ஏற்பட்டதைத் தொடர்ந்து விஞ்ஞானச் சிந்தனையாளர்களிடையே வெவ்வேறுபட்ட கருத்து வேறுபாடுகள், முரண்பாடுகள் தோற்றம்பெறுகின்றன. ஆனாலும் கூனின் நோக்கில் விஞ்ஞானத்தின் வளர்ச்சி, அதன் முன்னேற்றம் என்பது காலமாற்றங்களுக்கேற்ப வெவ்வேறுபட்ட கருத்துப்பரிமாணங்களுடன் வளர்ச்சி கண்டு வருவதே ஒழிய நிச்சயமாக உறுதிப்படுத்தப்பட்ட ஒன்றல்ல எனக் குறிப்பிட்டார்.

இதற்கு எடுத்துக்காட்டாக, வானியல் ஆராய்ச்சியில் ஈடுபட்டுப் பல புதிய உண்மைகளை வெளிக்கொணர்ந்தவர்களில் கொப்பனிக்கசும் அவருடைய சூரியமையக் கொள்கையும் குறிப்பிடத்தக்கதொன்றாகும்.

விஞ்ஞான ஆராய்ச்சிகளிலிருந்து ஏற்கனவே முன்மொழியப்பட்ட பழைய கட்டளைப்படிமத்திலிருந்து முற்றிலுமோ பகுதியளவிலோ மாறுபட்ட அல்லது பொருந்தாத கருத்தமைப்புக்களைக்கொண்டு உருவாக்குவது புதிய கட்டளைப்படிமமாகும். இதுவே புதிய விஞ்ஞானப் புரட்சிக்கு அடிப்படையாகும். மேற்குறிப்பிட்ட மாற்றங்களின்போது பழைய கட்டளைப்படிமம், புதிய கட்டளைப்படிமம் ஆகிய இரண்டிற்கும் பொதுவானதொரு தர அடிப்படை அளவுகோள் (ஒத்திசைவின்மை - Incommensurability) கிடையாது என்பதனைக் கூன் சுட்டிக்காட்டினார். கூனின் மேற்குறித்த சிந்தனையை தெளிவுபடுத்தும் பெயராபெண்ட், விஞ்ஞானம்சார் பிரச்சினைகளை ஆராய்கின்ற விஞ்ஞானி அப்பிரச்சினைக்குத் தனிச்சிறப்பியல்பான ஆய்வு முறையியல் ஒன்றைக் கையாண்டிருப்பர். இவ்வாய்வு முறையியல் பிரச்சினைக்குப் பிரச்சினை வேறுபடுவதால் ஆய்வினால் உருவாக்கப்பட்ட விஞ்ஞானக் கொள்கைகளும் இயல்பில் ஒன்றிலிருந்து ஒன்று வேறுபடுகின்றன. இதனால் அவற்றை ஒப்பிடமுடியாது எனக் கூறினார். பெயராபெண்டின் இத்தகைய சிந்தனை கூனின் முறையியற் சிந்தனைக்கு வலுச்சேர்ப்பதாக அமைகின்றது.

மேலும், இரண்டு கட்டளைப்படிமங்கள் ஒன்றையொன்று ஒப்பிட்டுக் கூறமுடியாது என்பது பற்றி கூன் பின்வரும் அடிப்படையில் விளக்குகிறார்;

1. கட்டளைப்படிமங்களுக்கு பொதுவான அளவீடு என ஒன்றுமில்லை. ஏனெனில் மதிப்பீடுகளும் ஒப்பீடுகளும் மாற்றமடைந்து செல்வதனாலேயேயாகும். இந்தவகையில் விஞ்ஞானத்தில் மாற்றமடையாத கட்டளைப்படிமம் என ஒன்றிருக்கமுடியாது. இத்தகைய நிலைப்பாடே விஞ்ஞானப் புரட்சிக்கு வழிவகுக்கின்றன.

2. விஞ்ஞானத்தில் கட்டளைப்படிமம் என்ற முறையியற் சிந்தனை புலக்காட்சி, அவதான மொழி என்பவற்றின் மூலம் அர்த்தம் பெறுகிறது. இருந்தும், புரட்சியினை ஏற்படுத்துகின்ற கட்டளைப்படிமம் புலக்காட்சியினைப் போன்று பருமட்டான விடயங்களையும் கூட மாற்றுகின்றன. ''புரட்சியின் பின்பு விஞ்ஞானிகள் முகம் கொடுப்பது வேறொரு உலகத்திற்கே, அதாவது புரட்சிக்கு முன்பு விஞ்ஞானிகளின் உலகிலிருந்த அன்னங்கள் புரட்சியின் பின்பு முயல்களாகின்றன'' என கூன் விளக்கினார்.

ஆக, புரட்சிக்கு முன் அன்னங்களாக இருந்தவை புரட்சிக்குப் பின் முயல்களாக மாறலாம் எனக் கூன் கருதுவது உலக நோக்க மாற்றத்தினையேயாகும். எனவே விஞ்ஞானப் புரட்சியானது நேர்வுகள் அல்லது நிகழ்வுகள் தொடர்பிலான உலக நோக்கினை மாற்றியமைப்பதாக அமைகின்றது. விஞ்ஞானிகள் காலத்திற்குக் காலம் தமது கருத்துக்களில் மாற்றங்களை ஏற்படுத்திக்கொள்கின்றனர். விஞ்ஞான அறிவு வளர்ச்சியில் வரலாற்று ரீதியாக மாற்றங்கள் நடைபெறுவதனால் சாதாரண காலத்திலிருந்த அறிவு பற்றிய நோக்கும் புரட்சியின் பின்னரான அறிவு பற்றிய நோக்கும் வெவ்வேறுபட்டதாக அமையும் என்பதனையே மேற்குறித்த விளக்கங்கள் தெளிவுபடுத்தி நிற்கின்றன.

எனவே, தொகுத்து நோக்கும்போது, இரண்டு கட்டளைப்படிமங்களிற்கிடையில் ஒத்திசைவின்மை காணப்பட்டபோதிலும் விஞ்ஞானத்தில் புரட்சியினூடாகப் புதிய கட்டளைப்படிமம் எழுச்சிபெறுவதற்குப் பழைய கட்டளைப்படிமம் உறுதுணையாக விளங்குகின்றது என்று

கூறிக்கொள்ளலாம். இதன்படி பழைய கட்டளைப்படிமம் ஆராய்ச்சிக்காக எடுத்துக் கொள்ளப்படுமே தவிர ஆய்வின் முடிவன்று. இதனடிப்படையிலேயே ஒத்திசைவின்மை என்ற கருத்தியல் கையாளப்படுகிறது.

விஞ்ஞானங்களில் கட்டளைப்படிமம் பற்றிய சிந்தனை

கூன் தமது ஆய்விற்குரிய பொருளாக இயற்கை விஞ்ஞானத்தை அடிப்படையாகக்கொண்டு விஞ்ஞானத்தின் வரலாறு, அதன் வளர்ச்சிப்போக்கினை ஆய்விற்குட்படுத்தினார். இவ்வியற்கைத் தோற்றப்பாட்டியியலில் ஆய்விற்குட்படுத்தாத பல விடயங்கள் காணப்படுகின்றன. அத்தகைய விடயங்களையே விஞ்ஞானிகள் தெளிவுபடுத்தி ஆய்வுசெய்ய முற்படுகின்றனர். இதனாலேயே விஞ்ஞானத்தின் முன்னேற்றமானது பரிணாம ஒழுங்கில் செல்கின்றதோடு புதிய உண்மைகளும் வெளிக்கொணரப்படுகின்றது. இப்பின்னணியிலேயே கட்டளைப்படிமம் என்ற முறையியற் சிந்தனை தாக்கம் செலுத்துகின்றது.

விஞ்ஞான முறையியல் வளர்ச்சியில் கூன், இயற்கை விஞ்ஞானத்தை விடுத்து சமூக விஞ்ஞானத்தில் உறுதியான கட்டளைப்படிமங்கள் தோன்றவில்லை எனக் குறிப்பிட்டார். இக்கட்டளைப்படிமங்கள் தோன்றாமையே சமூக விஞ்ஞானங்கள் துரிதமாக வளர்ச்சியடையாமைக்குரிய காரணமாகும். சமூக விஞ்ஞானம் என்பது மனித சமூகத்திலுள்ள அங்கத்தவர்களின் பண்புகள், நடத்தைக் கோலங்கள் தொடர்பாக ஆய்வு செய்வதாகும். இவ்விஞ்ஞானத்தில் ஆராய்பவனும் ஆய்வுப் பொருளும் மனிதனாவான். இவனது நடத்தைக் கோலங்கள் காலத்திற்குக் காலம், இடத்திற்கு இடம் மாற்றமடையும் போக்கினைக்கொண்டது. இதனால் எல்லோராலும் ஏற்றுக்கொள்ளக்கூடிய பொதுமைப்பாடான முடிவை அல்லது உண்மையினைப் பெற்றுக்கொள்வதில் சிக்கல்கள் ஏற்படுகின்றன. இத்தகைய நிலைப்பாடு உறுதியான கட்டளைப்படிமங்கள் தோன்றுவதற்கு சாத்தியமற்ற சூழ்நிலையை உருவாக்குகின்றது. இதனாலேயே ஜே.எஸ். மில் போன்றோர்கள் மனிதனின் சொந்த இயல்பையும் அவன் வாழும் சமூகத்தின் இயல்பையும் பற்றிய அறிவு மிகவும் பிற்போக்குத்தனமானது எனக் குறிப்பிட்டதன் தாற்பரியமாகும்.

விஞ்ஞானத்தில் அனுபவச் சோதனைகளே உண்மையைக் கண்டறிவதற்கான திறவுகோல் என்பதனை விஞ்ஞான ஆய்வுகளிலிருந்து அறிந்துகொள்ளலாம். இச்சோதனைகளின் மூலமே கட்டளைப்படிமம் ஒன்றானது நிர்ணயமாகிறது. இதற்குச் சான்றாக, டால்ரனின் அணுக் கோட்பாடு, ஐன்ஸ்ரைனின் சார்புக் கோட்பாடு என்பவற்றைக் குறிப்பிடலாம். சமூக விஞ்ஞானங்களில் அனுபவச் சோதனைகளைக் குறிப்பாக பரிசோதனைகளைக் கையாள்வதில் இடர்பாடுகள் ஏற்படுகின்றன. மனித நடவடிக்கையும் சமூக நடவடிக்கையும் சிக்கலானவை. இதனால் அவற்றை பரிசோதனை மூலம் கட்டுப்படுத்தி ஆய்வு செய்வதென்பது கடினமானதொன்றாகும். இத்தகைய சிக்கல்களுக்கு முகம் கொடுப்பதனால் சமூக விஞ்ஞானத்தில் உறுதியான கட்டளைப்படிமங்களைப் பெற்றுக்கொள்வதில் இடர்பாடுகள் ஏற்படுகின்றன. தொடர்ந்து, இருபதாம் நூற்றாண்டுகளில் சமூக விஞ்ஞானங்களில் புலனறிவாதச் சிந்தனை (Positivism) ஆதிக்கம் செலுத்தியதைத் தொடர்ந்து விஞ்ஞான அறிவினைப் பெற்றுக்கொள்வதில் சாத்தியமான நிலையும் ஏற்படலாயிற்று.

மேற்குறித்த காரணங்களைத் தொகுத்து நோக்கும்போது, விஞ்ஞான அறிவு வளர்ச்சி மற்றும் தொழிநுட்பத்தின் பயன்பாடு போன்றவற்றினால் சமூக விஞ்ஞானங்களில் ஓரளவிற்கேனும்

ஏற்றுக்கொள்ளக்கூடிய பொதுமைப்பாடான உண்மையைப் பெற்றுக்கொள்வதில் சாத்தியம் ஏற்படலாயிற்று என்றே கூறிக்கொள்ளலாம்.

பிரயோகத்தன்மை குறித்த நோக்கு

விஞ்ஞான வரலாற்றில் அதன் வளர்ச்சியானது நேர்கோட்டில் செல்வதில்லை. பழைய அறிவிலிருந்து தோன்றுகின்ற புதிய அறிவு, பழையதை உள்வாங்கியும் அதேவேளை அதை மறுதலித்துமே வளர்ச்சியடைகின்றது. ஒருவகையில், அவ்வளர்ச்சியானது இயக்க விதியின் பாற்பட்டதாகும். இவ்வுண்மையை எளிமைப்படுத்தி விஞ்ஞான வரலாற்றையும் விஞ்ஞானக் கண்டுபிடிப்புக்களுக்கான வாய்ப்புக்களையும் தெளிவுபடுத்துதல் அவசியமானதொன்றாகும்.

இப்பின்னணியிலேயேதான் கூனின் கட்டளைப்படிம மாற்றம் பற்றிய முறையியற் சிந்தனையானது பிரக்ஞை பூர்வமான சிந்தனையைத் தூண்டுவித்தலில் கூடுதல் தாக்கம் செலுத்துகின்றது. எனவேதான் மேற்குறித்த முறையியற் சிந்தனைகளையும் அதன் வளர்ச்சிப் படிநிலைகளையும் தெளிவாகப் புரிந்துகொள்வதன் மூலம் புதிய ஆய்வினை அல்லது புதிய உண்மையை வெளிக்கொணர்வது என்பது சாத்தியமாகின்றது.

குறிப்பாக, வரலாற்று நோக்கில் ஏற்கனவே உள்ள கொள்கைகள் அல்லது விதிகளைப் பற்றி தெளிவாக அறிந்துகொள்வதோடு அவற்றைப் பிரயோகித்து மேலும் பல புதிய சிந்தனைகள், உண்மைகளை வெளிக்கொணர்வது அறிவின் பாய்ச்சலாகும். இத்தகைய முன்னோக்கிய பாய்ச்சலில் அறிவினை நகர்த்துதல் வேண்டும். இதன்மூலம் விஞ்ஞானச் சமூகத்தினை உருவாக்கிப் புதிய சிந்தனைகளை அல்லது உண்மைகளை வெளிக்கொணரச் செய்தல் வேண்டும். மேற்குறித்த நிலைப்பாடு பின்வரும் அடிப்படையில் அமையலாம் எனப் பரிந்துரைக்கப்படுகின்றது.

- விஞ்ஞானச் சமூகத்திற்குத் தேவையான கண்டுபிடிப்புக்களை அல்லது புதிய சிந்தனைகளை உருவாக்க முனைய வேண்டும்.
- எந்தவொரு நிகழ்வையும் துல்லியமாகக் கணிப்பதற்கான சிந்தனையை வளர்க்க உதவுதல் வேண்டும்.
- வெறும் கோட்பாட்டறிவோடு நின்றுவிடாமல் அதனைப் பிரயோகிக்கின்ற விஞ்ஞானச் சமூகத்தினை உருவாக்குதல்.
- கோட்பாட்டறிவினை மீள்கட்டமைப்புச் செய்வதற்கான அறிவினை வளர்க்க உதவுதல்.
- முறையியற் சிந்தனைகளைப் பயன்படுத்திப் புதிய உத்திமுறைகளைக் கையாண்டு அவற்றைப் பிரயோகிக்க உதவுதல்.

முடிவுரை

கூனினுடைய நோக்கில் விஞ்ஞானத்தின் வளர்ச்சி, முன்னேற்றம் என்பன காலமாற்றங்களுக்கேற்ப வெவ்வேறு கருத்துப் பரிமாணங்களுடன் வளர்ச்சி கண்டு வருவனவே ஒழிய நிச்சயமாக உறுதிப்படுத்தப்பட்டனவல்ல எனக் குறிப்பிட்டார். இதனையே அவரது கட்டளைப்படிம மாற்றம் பற்றிய சிந்தனையினூடாக வலியுறுத்தியிருந்தார். கூனின் இம்மாற்றம் பற்றிய சிந்தனை விஞ்ஞானம் மட்டுமல்ல சகல துறைகளையும் உள்வாங்கியிருந்தது. வரலாற்றில் எந்தத் துறையாக இருந்தாலும் ஏற்கனவே புதிது புனையப்பட்ட விடயங்களை முடிந்த முடிவாக ஏற்றுக்கொள்வதை விடுத்து மேலும் புதிய, புதிய உண்மைகளை வெளிக்கொணருதல் வேண்டும். அவற்றின் மூலமே விஞ்ஞான அறிவு

மேனோக்கிய பாய்ச்சலினூடாக வளர்ச்சியடைந்து செல்லும் என்பது ஆய்வின் மூலம் வெளிக்கொணரும் உண்மையாகும்.

குறிப்பாக, விஞ்ஞான அறிவைப் பொறுத்தவரையில் முடிவிலியாகத் தொடரும் தேடலில் பழைய கட்டளைப்படிமம் மயற்றமடைந்து புதிய கட்டளைப்படிமம் தோற்றம்பெற்றுக்கொண்டே இருக்கின்றன. இதன்பேறாக விஞ்ஞான அறிவும் இயங்கியல் அடிப்படையில் வளர்ச்சியடைந்துகொண்டு செல்கின்றது. எனவே 'கட்டளைப்படிம மாற்றங்களினூடாகவே' விஞ்ஞான வளர்ச்சியடைந்து செல்கின்றது என்ற கூனின் சிந்தனைக்கு செயல்வடிவம் கொடுப்பதாக அமைகின்றது.

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Harnessing Agricultural Technologies for Sustainable Development in Northern Province

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The Northern Province, endowed with fertile lands and a significant portion of the population engaged in farming, holds great potential for agricultural development. However, to achieve sustainable development, it is crucial to adopt innovative agricultural technologies that can enhance productivity, ensure food security, and promote environmental sustainability.

Introduction to the Agriculture Sector in Northern Province

The agriculture sector in the Northern Province is the backbone of the regional economy. With a population of approximately 1.26 million and 149,136 farm families, the province's agricultural landscape is vast and diverse. The total cultivable land spans 181,965 hectares, with significant areas dedicated to paddy and highland cultivation. The region's agriculture contributes substantially to both provincial and national GDP, highlighting its importance in the broader economic framework.

Needs for Sustainable Agriculture Development

For sustainable agriculture development in the Northern Province, several critical needs must be addressed. Firstly, ensuring food and nutrient security for the general population is paramount. This involves increasing crop yields and diversifying agricultural produce to meet dietary requirements. Secondly, ensuring the income security of the farming community is essential. By enhancing productivity and reducing production costs, farmers can achieve better economic stability. Additionally, increasing income from agricultural exports and reducing the import of agricultural produce are vital for economic growth.

Environmental sustainability is another key need. Protecting natural resources for future generations through environmentally friendly farming practices is crucial. Climate-smart agriculture, which involves adopting practices that mitigate the effects of climate change, is necessary. Market-oriented commercial agriculture can improve the profitability of farming, while informed behavioral changes in consumption patterns can support sustainable agriculture. Lastly, safeguarding the marketing of agricultural produce ensures fair pricing and reduces exploitation of farmers.

Constraints in Achieving Sustainable Development

Achieving sustainable development in the Northern Province is not without challenges. One of the major constraints is the deterioration of soil fertility. Overreliance on chemical fertilizers, neglect of organic manure, and failure to adopt soil test-based recommendations have led to soil degradation. Fertile lands being converted for non-agricultural purposes, such as housing and commercial developments, further exacerbates the issue. Fragmentation of lands generation after generation also hinders large-scale agricultural operations. The high cost of production is another significant constraint. The rapid increase in input costs, higher prices for fuel, electricity, seeds, machinery, and labor make farming less economically viable. Unfavorable climate change, characterized by irregular rainfall patterns, floods, and droughts, poses additional challenges. Scarcity of quality water for irrigation due to overexploitation and poor water management practices further limits agricultural productivity.

The migration of human resources from agriculture to other sectors and countries results in a labor shortage. Potential farmers migrating abroad, young children disinterested in agriculture, agricultural laborers seeking jobs in other sectors, and agriculture professionals migrating to other countries contribute to this issue. Non-adoption of innovative agricultural technologies due to lack of awareness and access also impedes progress towards sustainable development.

Agricultural Technologies for Sustainable Development

To overcome these constraints and achieve sustainable development, the adoption of advanced agricultural technologies is crucial.

Improve Soil Fertility

Improving soil fertility is fundamental to sustainable agriculture. This can be achieved by producing and applying enriched organic fertilizers. Regular soil analysis and appropriate management of fertilizers ensure efficient nutrient use. Implementing Integrated Plant Nutrient Systems (IPNS), such as precision agriculture and nano fertilizers, promotes balanced nutrient application. The application of bio-fertilizers, compost, green manure, livestock dung, and agricultural waste enhances soil health.

Prevent Conversion of Fertile Land

Preventing the conversion of fertile land for non-agricultural purposes is essential. Formulating and enforcing laws to protect cultivable high land and developing strategies to address land needs for other purposes can help preserve agricultural land. Consolidating cultivable land to make cultivation economically viable is also necessary. Encouraging entrepreneurs to consolidate unproductive land through long-term leasing or procurement can optimize land use. Consolidating small land lots and leveling them using laser technology for commercial-scale cultivation ensures efficient land management.

Reduce Cost of Production & Increase Productivity

Reducing the cost of production and increasing productivity are critical for sustainable agriculture. Producing and using quality seeds for crops like paddy, vegetables, and other field crops (OFC) enhance crop yields. Encouraging the production of true seeds, seedlings, and hybrids for crops like onions, chilies, and maize improves crop quality. Promoting seedling production and crop establishment as a business can further reduce costs. Utilizing agricultural machinery and equipment, such as drones for sowing, fertilizing, and pest control, increases efficiency and reduces labor requirements.

Promote Protected Agriculture

Protected agriculture, which involves cultivating crops in controlled environments, can significantly enhance productivity. Growing crops in insect-proof netted fences with micro irrigation systems and mulch films reduces pest damage and conserves water. Engaging in off-season vegetable cultivation in poly tunnels and net houses ensures year-round production. Growing crops in raised beds with mulch films improves yield and quality by providing better soil conditions and reducing weed growth.

Increase Usage of Renewable Energy Equipment

Increasing the usage of renewable energy equipment in agriculture is vital for sustainability. Deploying solar water pumps, powered sprayers, animal repellents, and sticky traps reduces dependence on fossil fuels and lowers operational costs. Utilizing biogas systems for energy production from agricultural waste provides a sustainable energy source and reduces waste disposal issues.

Enhance Efficient Irrigation Systems

Efficient irrigation systems are crucial for optimal water use. Implementing sprinkler and drip irrigation systems, rain gun sprays, and drum drip methods ensures precise water application. Harvesting rainwater and rehabilitating existing ditches enhance water availability and reduce the impact of water scarcity on crop production.

Integrated Pest Management (IPM)

Integrated Pest Management (IPM) practices help manage pest and disease issues sustainably. Using pest-free seeds, mixed cropping, and life fences reduces pest pressure. Applying bio-pesticides, botanical pesticides, and releasing parasitoids provide eco-friendly pest control. Resorting to chemical pesticides only as a last measure ensures minimal environmental impact.

Overcome the Effects of Floods and Droughts

To mitigate the adverse effects of floods and droughts, several strategies can be employed. Cultivating crops in ridges and developing drainage systems manage floodwater effectively. Seed hardening, seed treatment, mulching, and micro irrigation systems help combat drought. Constructing water harvesting ponds and rehabilitating existing ditches improve water availability during dry periods.

Attract Youth to the Agriculture Sector

Attracting youth to the agriculture sector is essential for its long-term sustainability. Transforming farming into a business can make it more appealing to young entrepreneurs. Conducting skill development courses and training for youth enhances their agricultural expertise. Increasing the intake of students in agricultural vocational courses and promoting the use of farm machinery can further attract young people to agriculture. Establishing machinery hiring centers and introducing new farm technologies provide support for modern farming practices.

Conclusion

Harnessing agricultural technologies for sustainable development in the Northern Province is essential for achieving food security, economic growth, and environmental sustainability. By addressing the challenges and leveraging innovative solutions, the region can pave the way for a prosperous and sustainable future in agriculture. The adoption of advanced technologies, protection of natural resources, efficient water management, and engagement of the youth in agriculture are key to transforming the agricultural landscape of the Northern Province.

Nature's Blueprint: Shaping the Future of Industry through Fundamental Science

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Nature's Blueprint: Shaping the Future of Industry through Fundamental Science. Researchers identify the common scientific issues that now these days we faced and try to solve the problem through fundamental research. The success of Fundamental researches leads to commercialization of desired products. However, the adverse biproducts may to accumulate in the earth or the production path may lead to release adverse environmental pollutants and may affect the environmental health. Most of the industrial process relay on the fossil fuel to get the energy. Further, excessive usage of pesticides and herbicides in agriculture, usage of different dues in garment industries, over usage of plastic particularly single use and throw, and chemical industrial process may significantly affect the environmental health. As its consequences, scientist scrutinize the path of invention by observing and understanding how nature solves problems and mimic it to develop new technologies and solutions that are more efficient, sustainable, and innovative called biomimicry.

Biomimicry not only provides new ideas but also promotes sustainability by encouraging solutions that are compatible with natural processes. Even though, there are numerous research and considerable efforts performed by the scientist, has not being able to achieve the same level of diversity and functionality found in nature. A lot more needs to be done to get closer to nature. For examples, energy storing like photosynthesize, brain of one person can, in principle, store and process more information than today's computer, water purification and storage and olfactory receptors of the dog are much more sensitive than the sensors etc. Further, scientist inspired by observing and studied the shark skin, such as how it reduces the wall shear stress, and reduction in drag force. Biomimicry those ideas and improve their design in reduction of fluid flow around the ships and aeroplanes. Superhydrophobic nature of lotus leave repel the water and shows self-cleaning properties. Mimic the natures invention and try to produce Superhydrophobic nature and self-cleaning properties with clothes and shoes etc. to sophisticate life style. Simulation and Optimization Study on the Ventilation Performance of High-Rise Buildings Inspired by the White Termite Mound Chamber Structure, inspired natural ventilation systems that regulate temperature without external energy sources. In robotics, the study of animal locomotion has led to the creation of robots that can navigate challenging terrains, providing valuable tools for exploration and disaster response.

Materials science is also benefiting from nature. Scientists are developing biodegradable plastics from plants to reduce plastic pollution. using bioplastics can help mitigate climate change by reducing CO_2 emissions and other greenhouse gases. The chicken-feather chip is made from soybean resin and feathers crafted into a composite material that looks and feels like silicon. In early tests, electrical signals moved twice as quickly through the feather chip as through a conventional silicon chip, researchers said. looks at the microscopic structure of spider silk and reveals unique characteristics in the way it transmits phonons, quasiparticles of sound. These materials are biomimicry and use for medical stitches and bulletproof vests.

Green chemistry is another area where nature is guiding industry, focuses on designing products and processes that minimize the use and generation of hazardous substances and other benefits. Not only minimize the hazardous substances, it provides better guidance to sustainable and toxic free alternative to better man of human and environmental health. In green synthesis of materials or substance, one or more chemicals or solvents substitute by naturally available material and use of hazardous substances minimized. For example, in green synthesize of nanomaterial the plant or leave extract which consist polyphenolic acid use as surfactant and reducing agent and it eliminate the use of synthetic chemicals for the same purpose.

Polylactic Acid (PLA) is a biodegradable polymer derived from renewable resources like corn starch or sugarcane. It is used in various applications, including packaging, disposable tableware, and medical devices, providing an eco-friendly alternative to petroleum-based plastics. The primary source of pollutants arises in the industry due to consumption of fossil fuel. The substituent of fossil fuel by naturally available renewable energy sources such as solar power, wind energy, hydropower etc, mitigate to alleviate numerous environmental health issues.

Natural photosynthesize, inspired innervation to harvest solar light. The intricate structures of butterfly wings have inspired the design of more efficient solar cells. Butterfly wings have tiny scales that can trap light and enhance its absorption. By mimicking these structures, scientists have created solar cells with nanostructures that increase light absorption and improve efficiency. Leaves are highly efficient at capturing sunlight. Solar cells designed to mimic the shape and surface texture of leaves can capture more light and convert it into energy more effectively. These bio-inspired designs also allow for better cooling and increased durability. Researchers are studying the light-harvesting complexes found in plants and bacteria to develop quantum dots that mimic these natural processes. Moth eyes have a unique structure that prevents reflection and allows them to see well in low light conditions. This structure has inspired antireflective coatings for solar cells. By applying these coatings, solar cells can reduce reflection and capture more sunlight, improving their overall efficiency.

Utilizing solar energy has many benefits including sustainability, reduction of greenhouse gases, energy security, economic benefits etc. However, there are certain challenges and considerations available based on intermittency, energy storage, initial costs, land use and environmental impact.

Conclusively, fundamental science, and basic research, is essential as it provides the foundational knowledge that applied science and technology build upon. Fundamental research leads to the discovery of new principles and phenomena. Interdisciplinary collaboration involves the integration of knowledge and methodologies from different disciplines to solve complex problems. The insights gained from interdisciplinary collaboration and nature's blueprint can revolutionize industries.

Innovative and Sustainable Food Technologies

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Introduction

The global food system is confronting critical challenges that require immediate and transformative action. Feeding a fast-growing world population, which is expected to reach almost 10 billion by 2050 (United Nations, 2022), while protecting the limited resources of the Earth has emerged as one of the most pressing challenges of the current era. Problems such as climate change, shrinking farmland, water shortages, loss of biodiversity, and growing inequalities are making it even more important to rethink the way the food is produced, distributed, and consumed. In this context, adopting innovative and sustainable food technologies is crucial for creating a healthier, fairer, and more sustainable future. In the fields of food processing, agriculture, food production, and distribution, increasing attention is being given to waste reduction, material recycling, and the reuse of energy, water, and by-products. Businesses and industries within the agri-food sector are becoming increasingly aware of the need to use resources more efficiently to reduce environmental impact and enhance global food security.

Contemporary food technologies encompass a wide range of innovations aimed at improving food production, processing, packaging, and sustainability across the agri-food sector. These innovations are driving systemic change, enabling the food sector to increase efficiency, reduce environmental impacts, enhance nutritional quality, and create more inclusive food systems. Importantly, the convergence of food innovation, food security, and sustainability offers an opportunity to address the global goals, including the United Nations Sustainable Development Goals (SDGs), particularly those related to zero hunger, good health and well-being, responsible consumption and production, and climate action.

However, despite the promise of these technologies, numerous challenges remain. Issues related to regulatory frameworks, consumer acceptance, ethical considerations, economic barriers, and scalability continue to impede the widespread adoption of sustainable food solutions. Therefore, understanding the dynamic interplay between technological innovation and systemic transformation is critical. This article explores the vital intersection between food innovation, food security, and sustainability; highlights the cutting-edge technologies reshaping the food landscape; examines the obstacles that must be overcome; and proposes strategic pathways for fostering an inclusive, sustainable, and innovative food future.

The global food system

The current global food system reveals stark inequalities and inefficiencies (FSIN and Global Network Against Food Crises, 2024).

- Hunger: Up to 780 million people around the world experience hunger daily.
- Food waste: Approximately 1.26 billion people could be fed with the food that is lost or wasted each year.
- Resource inefficiencies: Roughly 30% of all food produced globally is either lost or wasted.

While hunger and food waste are pressing concerns, the environmental impact is equally alarming:

- ¼ of global greenhouse gas emissions are attributed to food production.
- 60% of biodiversity loss since the 1970s is linked to agriculture and food systems.

These figures highlight the urgent need to transform the food system into a more innovative and sustainable model to protect both human well-being and the health of the planet.

Food innovation, food security, and sustainability

Food innovation involves the creation of new products, processes, and technologies that tackle challenges within the food system. This includes improving food safety, enhancing nutritional value, minimizing waste, and supporting sustainability. Food security ensures that everyone has consistent access to enough safe and nutritious food. Innovation is essential in this context by boosting productivity, reducing food losses, and building more resilient food systems. A sustainable food system, aligned with the United Nations Sustainable Development Goals (SDGs), aims to produce food in an environmentally responsible, socially equitable, and economically viable manner. Achieving this vision requires holistic thinking and coordinated action across every stage of the food chain from farm to fork.

Innovative and sustainable food technologies

Several groundbreaking technologies are reshaping how food is produced, processed, packaged, and consumed. These techniques aim to tackle key challenges such as improving food quality (making it healthier and more nutritious), promoting sustainability, and boosting production efficiency. The following sections provide an overview of these techniques, their objectives, applications, and the associated challenges.

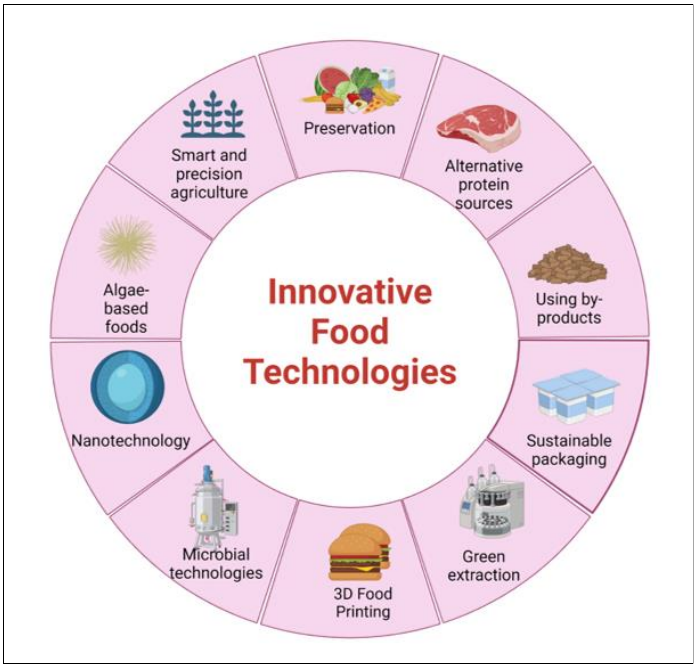

Figure 1: Innovative and sustainable food technologies (Created with BioRender.com)

Innovative food preservation techniques

In recent years, food preservation methods have been evolving from traditional thermal techniques toward innovative non-thermal technologies. This shift is driven by the need to maintain the nutritional and sensory quality of foods, reduce the reliance on chemical preservatives, and promote environmental sustainability. Non-thermal methods aim to inactivate microorganisms and enzymes responsible for spoilage without subjecting food to high temperatures, thereby preserving heat-sensitive nutrients and natural flavors more effectively.

- **High-Pressure Processing (HPP):** It is a non-thermal pasteurization method in which prepackaged products are placed into a vessel and exposed to extremely high isostatic pressures, typically ranging from 300 to 600 MPa. HPP provides numerous benefits, such as producing safe, minimally processed foods with extended shelf life, enhancing supply chain efficiency, reducing food waste, supporting clean label initiatives, offering versatility across products, promoting environmental sustainability, and enabling a wide range of applications (Houška et al., 2022). It has been widely applied in the preservation of juices, ready-to-eat meals, and seafood.

- **Pulsed Electric Fields (PEF):** Pulsed electric field (PEF) technology involves the application of high-voltage pulses between two electrodes to fluid or semi-solid foods. The electric field disrupts microbial cell membranes, effectively sterilizing the food without significant heat exposure. PEF is commonly applied in the processing of milk and dairy products, eggs, poultry, fruit juices, and other liquid foods to control microbial contamination. As one of the most promising non-thermal food preservation methods, PEF offers an efficient approach to mitigating biological hazards while maintaining the nutritional and sensory quality of foods (Ghoshal, 2023).

- **Cold Plasma:** Cold plasma treatment involves exposing foods to ionized gases at low temperatures, enabling effective microbial decontamination. This technique utilizes highly reactive gaseous species to inactivate microorganisms on food surfaces and packaging materials. Cold plasma has demonstrated significant potential in the treatment of fruits, vegetables, meats, and packaging surfaces (Farooq et al., 2023)

- **Ozonation:** Ozone has emerged as a promising food preservation technology, attracting considerable interest due to its strong oxidative properties, potent antimicrobial activity, and residue-free decomposition. Depending on the specific application, ozone can be applied at varying concentrations in either gaseous or aqueous forms. It is widely used not only for controlling the growth of microorganisms in vegetables, fruits, meat, and grain-based foods (Xue et al., 2023).

- **Ultrasound:** Ultrasound is a nonthermal method increasingly explored for food preservation, particularly for microbial and enzyme inactivation. However, its standalone application is limited due to the resistance of certain enzymes and bacterial spores. To enhance its effectiveness, ultrasound is often combined with other treatments such as heat and pressure (Ercan and Soysal, 2013).

    - Ultrasonication: Application of ultrasound at low temperatures, suitable for heat-sensitive products. However, it requires longer treatment times and higher energy input for effective inactivation. Temperature rise during treatment must be controlled.

    - Thermosonication: Combines ultrasound and moderate heat, resulting in more effective microbial inactivation than heat alone.

    - Manosonication: Combines ultrasound with moderate pressure at low temperatures, enhancing the inactivation of enzymes and microorganisms compared to ultrasound alone.

    - Manothermosonication: Integrates ultrasound, heat, and pressure, offering improved enzyme inactivation at lower temperatures and in shorter times compared to conventional thermal treatments.

- These combination treatments improve the efficiency of ultrasound for food preservation applications.

- **Ultraviolet (UV) radiation:** UV radiation is a non-thermal method that has recently been used to improve the safety and shelf-life of food by reducing harmful microorganisms. It is a type of non-ionizing energy, with the most effective germicidal range being UV-C (200–280 nm). UV light in general ranges from 100 to 400 nm and is classified into UV-A (315–400 nm), UV-B (280–315 nm), UV-C (200–280 nm), and UV-Vacuum (100–200 nm). Among these, UV-C is widely used for its strong ability to inactivate microbes. It works by damaging the genetic material (DNA) of pathogens, preventing them from multiplying and spreading (Chacha et al., 2021).

- **Ionizing Radiation:** Ionizing radiation is used in food processing to reduce microbial contamination and inhibit enzyme activity using gamma rays, X-rays, or electron beams. When radiation interacts with food molecules, it creates charged ions and highly reactive free radicals that disrupt microbial cells. There are three main types of ionizing radiation used: gamma rays from cobalt-60 or cesium-137, X-rays (up to 5 MeV), and electron beams (up to 10 MeV). Depending on the dose, the effects vary: *radicidation* (1–10 kGy) eliminates pathogens, *radappertization* (above 10 kGy) sterilizes foods like meat and spices, and *radurization* applies even higher doses to extend shelf life. Regulatory bodies consider doses up to 10 kGy safe and nutritionally adequate. The method works by damaging microbial DNA and generating reactive water molecules that lead to cell death, while generally preserving the physical and chemical properties of foods. Its effectiveness depends on factors like oxygen presence, food composition, and thickness (Chacha et al., 2021).

These non-thermal technologies significantly minimize the degradation of heat-sensitive vitamins, antioxidants, and bioactive compounds, extend shelf life, and contribute to reducing food losses across the supply chain. Their adoption supports the broader goals of building a sustainable and resilient food system, aligned with global efforts to achieve food security and environmental protection.

Innovative and sustainable food packaging

Food packaging has evolved far beyond its traditional role of merely protecting food from external contamination. Today, packaging plays a crucial part in supporting sustainability efforts across the food supply chain by reducing environmental impact, extending shelf life, and minimizing food waste. Emerging trends in sustainable packaging are driven by increasing consumer awareness, regulatory pressures, and the need for circular economy models in the food industry.

Breakthroughs in sustainable packaging include:

Biodegradable Packaging: Conventional food packaging, mainly made from fossil-based plastics, offers protection and shelf-life extension but poses significant environmental concerns due to its non-biodegradable nature. With global plastic use projected to triple by 2060, the need for sustainable alternatives is urgent. In response, biodegradable materials like PLA, starch-based polymers, and cellulose derivatives are gaining popularity for packaging fresh produce, dairy, and bakery products. These materials break down naturally through microbial action, reducing long-term waste. The shift from passive to active, eco-friendly packaging reflects a growing commitment to both food quality and environmental sustainability (Stoica et al., 2024).

Edible packaging: Edible packaging, made from food-grade proteins (e.g., casein, whey), lipids, and polysaccharides (e.g., alginate, pectin), is designed to be consumed with the food, reducing packaging waste, especially in single-serve applications. Driven by population growth, climate change, and the push for environmental sustainability, there is a growing demand for waste-free and durable packaging solutions. Edible packaging offers a promising alternative to conventional plastics by extending shelf life and decreasing reliance on petroleum-based materials (Nair et al., 2023).

Active, intelligent, and smart packaging: In addition to material innovations, active, intelligent, and smart packaging technologies are increasingly integrated into food packaging to enhance safety and quality. Active packaging interacts with food or its environment by incorporating additives that control moisture, oxygen, or microbial growth to extend shelf life. Intelligent packaging monitors the condition of food using indicators for freshness, temperature, or spoilage, providing real-time information during storage and transport. Smart packaging combines these features with digital technologies, offering active protection and tracking. These advanced systems are gaining traction as consumers and industries demand safer, longer-lasting food products (Biji et al., 2015).

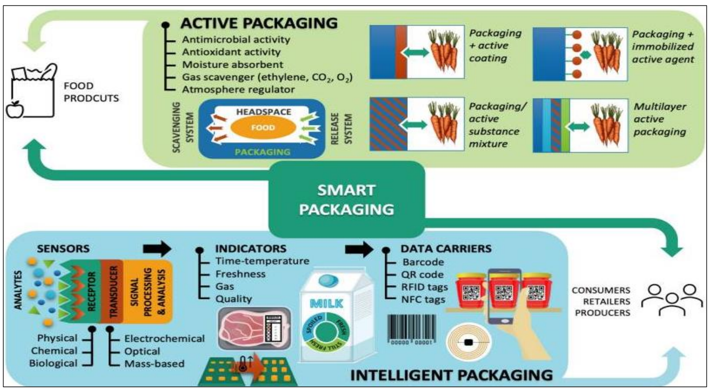

Figure 2: Active, intelligent, and smart packaging (Versino et al., 2023)

Overall, these innovations in food packaging are central to achieving a sustainable food system by addressing waste reduction, resource conservation, and consumer safety.

Green extraction techniques

Green extraction emphasizes the use of environmentally friendly, efficient, and sustainable methods for obtaining bioactive compounds from plants, agricultural wastes, and food industry by-products. These innovative techniques aim to minimize solvent consumption, reduce energy demands, and protect the integrity of heat-sensitive bioactive compounds such as antioxidants, polyphenols, essential oils, flavors, and colorants. Importantly, green extraction methods support the principles of the circular economy by transforming food waste streams into high-value ingredients for functional foods, nutraceuticals, and cosmetics.

Most commonly used green extraction techniques include:

- **Supercritical Fluid Extraction (SFE):** Supercritical fluid extraction, particularly using carbon dioxide (CO_2) as the solvent, is a highly efficient method for extracting non-polar bioactive compounds such as lipids, flavors, and pigments. Supercritical CO_2 behaves like both a gas and a liquid, allowing it to penetrate matrices and dissolve targeted compounds effectively at relatively low temperatures. This process reduces the need for organic solvents and preserves sensitive molecules. SFE has been widely applied for extracting essential oils, carotenoids, and polyunsaturated fatty acids.

- **Ultrasound-Assisted Extraction (UAE):** Ultrasound-assisted extraction uses high-frequency sound waves to create cavitation bubbles in a liquid medium. The collapse of these bubbles disrupts plant cell walls, enhancing the release of intracellular bioactive compounds into the solvent. UAE shortens extraction times, lowers solvent and energy requirements, and improves yields of thermolabile compounds like polyphenols, anthocyanins, and vitamins (Chemat et al., 2017; Zhan et al., 2022). UAE is particularly attractive for scaling up food waste valorization processes.

- **Microwave-Assisted Extraction (MAE):** Microwave-assisted extraction employs microwave energy to heat the moisture inside plant materials, causing cell rupture and facilitating the rapid release of target compounds. MAE is known for significantly reducing extraction times and solvent volumes while achieving higher extraction efficiencies compared to conventional methods. It is especially effective for recovering phenolic compounds, flavonoids, and pigments from agricultural residues and food processing by-products (Şahin and Kurtulbaş, 2024).

Each of these green extraction methods contributes to a more sustainable food system by enhancing resource efficiency, reducing environmental impact, and enabling the production of natural, clean-label ingredients. Moreover, the valorization of food waste aligns with global sustainability goals, supporting waste reduction, economic development, and innovation in the food and health sectors.

Utilization of food industry by-products

Utilizing food industry by-products represents a sustainable and innovative approach to modern food technology. Instead of discarding nutrient-rich residues from processing fruits, vegetables, cereals, or dairy, these by-products can be transformed into value-added ingredients such as dietary fibers, natural antioxidants, protein concentrates, or functional additives. This not only reduces food waste and environmental burden but also enhances the nutritional and economic value of food products. Embracing such circular practices supports the development of eco-friendly, resource-efficient food systems aligned with global sustainability goals.

Alternative protein sources

The rising global demand for sustainable, ethical, and nutritious food options has accelerated the development of alternative protein sources. Traditional livestock production is resource-intensive and associated with environmental degradation, greenhouse gas emissions, and ethical concerns. As a result, innovative protein technologies are being explored to meet future food security needs while minimizing ecological impact. Outlined below are key advancements in alternative protein technologies.

Plant-based Proteins

Plant-based proteins are increasingly accepted as meat alternatives due to their environmental and health advantages. Commonly sourced from legumes and grains, they reduce emissions and resource use while supporting diverse diets. Traditional options like tofu and tempeh have evolved into meat analogues that mimic the taste, texture, and appearance of real meat using technologies such as extrusion and fermentation. However, these products often rely on highly refined ingredients, leading to criticism over their artificial nature (Kyriakopoulou et al., 2021).

Emerging technologies enhancing plant-based protein development

- **Advanced texturization:** High-moisture extrusion and fermentation techniques are used to create fibrous, meat-like textures that enhance the mouthfeel and appeal of plant-based products.
- **Heme protein incorporation:** Some companies have developed soy leghemoglobin to replicate the iron-rich flavor of meat, giving plant-based burgers a "meaty" taste
- **Fat mimicry:** Innovations using structured plant oils and emulsions recreate the juiciness of animal fat, improving sensory properties in products like plant-based sausages and burgers.

- Three-dimensional (**3D) Printing:** 3D food printing is one of the most precise manufacturing technologies with a wide variety of applications. Emerging 3D food printing technologies enable the creation of complex, realistic meat analogs by layering plant-based ingredients in intricate structures.

Mycoprotein

Mycoprotein, derived from the naturally occurring fungus *Fusarium venenatum*, is a nutritious, meat-like protein alternative. Its production process results in a significantly smaller carbon and water footprint compared to beef and chicken. Quorn, a commercial mycoprotein is available in 17 countries, including the United States. It requires less land and water compared to livestock farming, contributing to sustainability goals. Mycoprotein offers significant nutritional, health, and environmental benefits, making it a valuable addition to a healthy diet (Finnigan et al., 2014).

Edible algae

Algae, being among the most diverse organisms on Earth, offer great potential for developing novel food products or replicating animal-based foods to address nutritional, environmental, and production challenges. Microalgae such as Spirulina and Chlorella are rich in nutrients, providing complete proteins, essential fatty acids, vitamins, and antioxidants. Their high protein levels, valuable lipids, and vital micronutrients make them promising additions to the human diet. Cultivating algae requires little land and freshwater, and they can be efficiently grown in closed bioreactors, which boosts yield and lowers contamination risks. As a result, algae-based proteins are increasingly used in snacks, drinks, and dietary supplements (Diaz et al., 2023).

Edible insects

Entomophagy, or the consumption of insects, is a traditional practice embraced by around two billion people across Africa, Asia, Latin America, and Oceania. Over 1,900 insect species are recognized as edible, offering nutritional, environmental, health, and economic benefits. Insects like crickets, mealworms, and locusts efficiently convert feed into protein while generating fewer greenhouse gas emissions and using significantly less land and water than conventional livestock. They are also rich sources of high-quality proteins, beneficial fats, vitamins, and minerals (Florença et al., 2022).

Lab-Grown Meat (Cultured Meat)

Lab-grown meat, also known as clean meat, in vitro meat, or cell-cultured/cell-cultivated meat, is produced by isolating cells from livestock and expanding them ex vivo to form cell biomass. This biomass can be used to create unstructured meat products, such as ground meat, or structured meat analogues by cultivating cells on scaffolds to mimic the texture of conventional meat cuts. The field of cultivated meat is rapidly expanding, with more than 100 companies worldwide working to commercialize and scale production. Despite strong financial investments and increasing interest from governments, several challenges persist. These include selecting suitable cell sources, developing cost-effective and cruelty-free food-grade media, ensuring scalable cell expansion, meeting regulatory requirements, and gaining consumer acceptance (Kirsch et al., 2023).

Use of algae in food and nutraceuticals

Algae, which include both microalgae (unicellular species) and macroalgae (commonly known as seaweed), are gaining recognition as essential elements of sustainable food systems. They offer substantial nutritional benefits while placing minimal demands on environmental resources, making them highly suitable for food and nutraceutical applications. Algae are rich in high-quality proteins that provide all essential amino acids, along with dietary fiber, polyunsaturated fatty acids, particularly omega-3s such as Eicosapentaenoic acid (EPA) and Docosahexanoic acid (DHA), vitamins such as A, B12, C, and E, as well as minerals including iodine, calcium, and iron. They also contain valuable bioactive compounds such as phycocyanins and polysaccharides. From an environmental perspective, algae can be cultivated in marine or brackish waters, reducing reliance on freshwater and eliminating the need for arable land. This allows for production in areas unsuitable for conventional agriculture, such as coastal zones and controlled photobioreactor systems. Additionally, algae contribute to carbon sequestration by absorbing atmospheric carbon dioxide, thereby supporting efforts to mitigate climate change. Compared to terrestrial crops, algae offer superior nutritional content and are produced through more environmentally sustainable methods (Kumari et al., 2023).

Applications

Algae are increasingly utilized in various sectors of the food industry due to their rich nutritional and functional properties. In food products, they are incorporated into snacks like roasted seaweed and algae chips, as well as pasta, bakery items, and protein bars to enhance nutritional value. In the dietary supplement market, microalgae like Spirulina and Chlorella are used in tablet, capsule, and powder forms for their high protein and antioxidant content, while algal oils rich in DHA and EPA offer plant-based alternatives to fish oils. Additionally, algae provide functional ingredients including bioactive compounds like sulfated polysaccharides, carotenoids, and polyphenols, known for their health-promoting effects. Hydrocolloids such as agar, carrageenan, and alginates extracted from macroalgae are also widely used in food processing as gelling, thickening, and stabilizing agents.

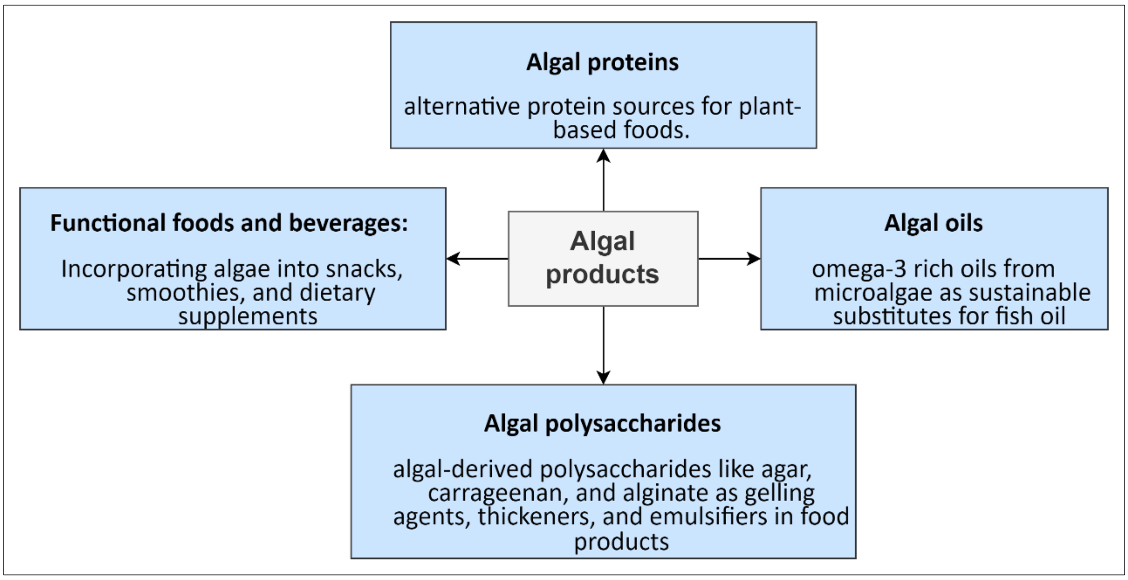

Figure 3: Innovative algal products

Constraints in the algal product industry

The versatility of algae in delivering high-value nutrients, functional benefits, and sustainability solutions places them at the forefront of food and nutraceutical innovations. Despite the recognized potential of algal biomass and the identification of numerous species, only a few are utilized in industrial-scale production. Macroalgae cultivation remains limited, with a significant portion still harvested from wild stocks. Factors such as small market size, inconsistent biomass supply, limited cultivation areas, suboptimal growth conditions, contamination risks, and high production costs hinder the expansion of the algal industry. Additionally, inefficient resource use and lack of valuable co-product recovery contribute to high manufacturing expenses. With continued advancements in cultivation, processing technologies, and consumer education, algae are poised to play a crucial role in shaping healthier diets and more resilient food systems worldwide.

Nanotechnology in food and nutraceuticals

Nanotechnology, the manipulation of materials at the nanoscale (1–100 nm), offers transformative potential in the food and nutraceutical sectors. Its applications aim to enhance food quality, improve safety, extend shelf life, and develop functional foods with superior health benefits.

Applications of nanotechnology

Nanoencapsulation: Nanoencapsulation is a technique that involves enclosing bioactive compounds—such as vitamins, probiotics, omega-3 fatty acids, polyphenols, and antioxidants—within nanocarriers made from lipids, proteins, or polysaccharides. This approach offers several benefits, including protection of sensitive ingredients from environmental degradation caused by factors like light, oxygen, and heat. It also enhances the solubility and stability of compounds that are poorly soluble in water. Furthermore, nanoencapsulation improves targeted delivery and enables controlled release of bioactives in the gastrointestinal tract, thereby significantly increasing their bioavailability and overall efficacy.

Nanosensors: Nanosensors are highly sensitive devices that utilize nanomaterials to detect biological and chemical changes within food systems. They offer several significant benefits, including the rapid and early detection of harmful pathogens such as *E. coli* and *Salmonella*, as well as toxins, allergens, and chemical contaminants. Nanosensors also enable real-time monitoring of food freshness and spoilage, helping to ensure quality and safety throughout the supply chain. Furthermore, they can be integrated into smart packaging, providing consumers with user-friendly alerts about the safety and condition of food products.

Nanocoatings: Nanocoatings involve the application of nanoscale edible or functional films onto food surfaces or packaging materials. These coatings offer several key benefits, including providing effective barriers against moisture, oxygen, and microbial invasion, which helps to extend shelf life and preserve food quality. Additionally, some nanocoatings are enhanced with antimicrobial agents, such as silver nanoparticles or essential oils, offering further protection against spoilage and contamination.

Nanoemulsions: Clear, stable emulsions at the nanoscale used for flavor delivery and incorporation of functional lipophilic ingredients.

Nanostructured lipid carriers: Advanced carriers that enhance the loading capacity and controlled release of bioactives compared to conventional emulsions or liposomes.

Nanotechnology aims to develop innovative and safe food formulations, including nanofoods that are non-toxic and suitable for human consumption. However, one of the main challenges is the lack of cost-effective methods for large-scale implementation. Therefore, there is a pressing need to focus on creating safe, biocompatible nanostructures from food-grade ingredients using simple and economical biological approaches. Despite current limitations, nanotechnology holds great promise for enhancing the quality and innovation of food products, making it a valuable tool in the modern food industry. However, responsible innovation, thorough safety assessments, and stringent regulatory oversight are crucial to ensuring the safe and sustainable integration of nanotechnology into the food sector (Gayathri et al., 2024).

Microbial technologies beyond traditional food fermentation

Microbial technologies are rapidly reshaping the landscape of food and nutraceutical innovation. While traditional fermentation processes such as those used in yogurt, cheese, sauerkraut, and bread have long contributed to food preservation, flavor enhancement, and basic probiotic benefits, the new generation of microbial technologies goes far beyond these conventional roles enabling the creation of new food products and ingredients, enhancing food safety, and deepening our understanding of gut microbiome interactions. Recent developments in this field have allowed for better control and use of these microbes, leading to innovations in traditional fermentation, sustainable ingredient production, food safety, and gut health research (Xia et al., 2023).

Advances in microbial technologies

- **Development of novel probiotics, enzymes, and functional ingredients**
  - **Next-generation probiotics:** Traditional probiotics such as *Lactobacillus* and *Bifidobacterium* species are now complemented by novel strains like *Akkermansia muciniphila*, *Faecalibacterium prausnitzii*, and *Christensenella minuta*, which have been associated with improved gut barrier function, anti-inflammatory effects, and metabolic health.
  - **Engineered microorganisms:** Advances in synthetic biology enable the design of genetically engineered microbes that produce targeted bioactive compounds like essential amino acids, vitamins, bioactive peptides, and even rare flavors and colors.
  - **Microbial enzymes**: New microbial enzymes offer enhanced performance for food processing, including improved dough stability, flavor development, and lactose reduction in dairy products.
- **Improved food safety via targeted microbial interventions**
  - **Biopreservation:** Specific beneficial microbes or their metabolites (e.g., bacteriocins) are used to inhibit spoilage organisms and pathogens naturally, extending shelf life without synthetic preservatives.
  - **Phage technology:** Bacteriophages (viruses that infect bacteria) are being used as highly specific biocontrol agents to target foodborne pathogens like *Listeria monocytogenes* and *Salmonella* without harming beneficial microbiota.
- **Enhanced understanding of gut microbiomes and their role in health**
  - **Microbiome-targeted foods:** With growing knowledge of how diet shapes the human microbiome, foods are now being developed to nurture beneficial gut bacteria through precision prebiotics and synbiotics.
  - **Personalized nutrition:** Microbial profiling of individuals' gut microbiota allows for the design of personalized dietary recommendations and functional foods aimed at improving specific health outcomes, such as metabolic syndrome, obesity, and immune health.

Despite promising advances in microbial technologies, several challenges persist. Regulatory hurdles must be addressed, particularly for genetically modified or engineered microorganisms. Consumer acceptance also remains a concern, especially when it comes to products developed through synthetic biology. Additionally, thorough safety evaluations are needed for novel microbial strains and their metabolites. Nonetheless, microbial technologies hold significant potential to contribute to global food security, public health, and sustainability.

Three-Dimensional (3D) Food Printing (Additive Manufacturing)

3D food printing, also known as additive manufacturing, represents a transformative advancement in food science and technology. Using layer-by-layer deposition of edible materials based on digital designs, this technology allows unprecedented customization of food structure, composition, and aesthetics. 3D food printing stands out as a highly precise manufacturing method with diverse applications. Current uses range from crafting intricate designs in candies, chocolates, and pasta to producing bio-printed meat alternatives. 3D printing offers promising advantages such as personalized nutrition, tailored textures, and the ability to meet individual dietary needs. This technology enables the creation of visually appealing, innovative food products and can produce custom textures for individuals with swallowing difficulties, such as dysphagia patients.

3D food printing contributes significantly to sustainability, customization, and inclusivity in modern food systems. It promotes environmental sustainability by utilizing alternative protein sources such as algae, insects, and plant-based proteins, while also minimizing food waste through on-demand, localized production. In terms of customization, this technology provides scalable solutions for creating personalized diets, particularly useful in settings like hospitals, elderly care facilities, athletic training centers, and space missions. Furthermore, 3D food printing enhances inclusivity by catering to the dietary needs of vulnerable populations, such as individuals with dysphagia, thereby improving their access to safe, nutritious, and enjoyable foods (Zhu et al., 2023).

Challenges and future prospects

While 3D food printing offers exciting potential for personalized nutrition and innovative food design, several challenges need to be addressed. Material limitations restrict the range of printable food ingredients, as food "inks" must possess specific rheological properties for successful printing. Additionally, the relatively slow production speed hinders scalability for mass production. Consumer skepticism toward highly engineered foods may also impact market acceptance. Moreover, food safety regulations for 3D-printed products are still developing, creating uncertainty for manufacturers. To overcome these hurdles, ongoing research is focused on enhancing printing technologies, broadening ingredient compatibility, and integrating nutritional optimization to fully harness the benefits of 3D-printed foods.

Precision agriculture

Precision agriculture, also known as site-specific crop management, utilizes advanced technologies to optimize farming inputs and boost productivity sustainably. Precision agriculture offers a promising solution to meet the increasing global food demand while promoting the sustainability of primary production by enabling more accurate, efficient, and resource-conscious management of crops and livestock. By tailoring practices to field-specific conditions, it minimizes waste and promotes environmental responsibility. Key technologies include sensors, drones, and GPS mapping, which provide real-time data for informed decision-making and precise field management. Artificial Intelligence (AI) plays a crucial role in analyzing trends, predicting crop needs, and improving decision-making through machine learning. This approach enhances resource efficiency through targeted application of water, fertilizers, and pesticides, reducing costs and environmental impact. Precision agriculture also contributes to increased crop yields, sustainability, improved food security, and economic benefits, positioning it as a transformative tool in the agricultural value chain (Monteiro et al., 2021).

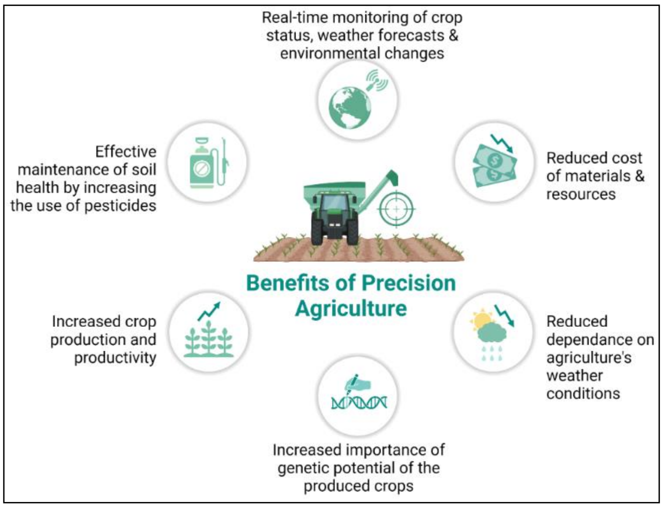

Figure 4: Benefits of precision agriculture (Created with BioRender.com)

Despite its promise, widespread adoption of precision agriculture faces hurdles such as high initial investment costs, technology accessibility for smallholder farmers, and the need for technical training. Future innovations, including low-cost sensors, open-source software platforms, and mobile-based advisory services, are expected to democratize access and further integrate precision agriculture into mainstream farming practices.

Challenges in innovative and sustainable food technologies

While innovative and sustainable food technologies offer immense potential to transform the global food system, their successful implementation faces several key challenges that must be addressed to realize widespread benefits.

Scalability: Many technologies, such as lab-grown meat production, advanced fermentation systems, and 3D food printing, have been demonstrated primarily at laboratory or pilot scales. The challenge lies in scaling up these innovations for mass production without compromising quality, safety, and efficiency. This process often requires significant infrastructure upgrades and production system redesigns, which can delay commercialization. Achieving a smooth transition from pilot to full-scale production is critical for these technologies to reach the market effectively.

Cost: High initial investment costs for equipment, research, and development present a major barrier, especially for startups and small-to-medium enterprises. Technologies like high-pressure processing and nanotechnology-enhanced food systems require expensive machinery and specialized expertise, which can make broader adoption difficult. These high costs limit the ability of smaller businesses to compete with larger corporations that have more resources for technological implementation.

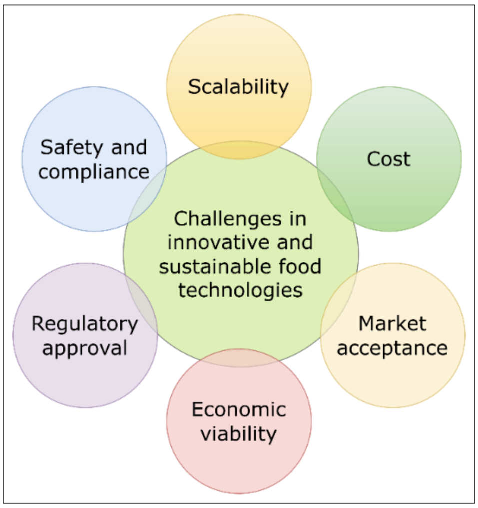

Figure 5: Challenges in innovative and sustainable food technologies

Market acceptance: Consumer skepticism toward unfamiliar foods, such as lab-grown meat, edible insects, and algae-based products, can significantly impede market growth. Acceptance of these new products depends on factors such as cultural perceptions, taste preferences, transparency in labeling, and the perceived naturalness of the food. Overcoming these barriers is essential to gain consumer trust and expand market acceptance, which is critical for the long-term success of these innovations.

Economic viability: For novel food products to achieve large-scale adoption, it is crucial that they are not only sustainable but also affordable. Balancing production costs while maintaining high-quality standards and competitive pricing is a core challenge, especially in developing economies. Ensuring that these products are economically viable, without relying too heavily on high production costs, is essential for widespread market penetration and long-term sustainability.

Regulatory approval: Novel food technologies must meet stringent regulatory frameworks concerning food safety, labeling, and environmental impact. However, these regulatory processes are often lengthy and vary across countries, creating uncertainty for innovators. This uncertainty can slow down market entry and delay the commercialization of new food products. Adhering to these complex regulations is essential for ensuring consumer safety and facilitating market approval.

Safety and compliance: Emerging technologies involving nanotechnology, genetic engineering, and advanced microbial applications require rigorous safety evaluations to protect consumers. Comprehensive risk assessments, long-term impact studies, and transparent communication are necessary to build public trust and regulatory confidence. Ensuring that these technologies comply with safety standards is vital for their acceptance in the market and for meeting public and regulatory expectations.

Way forward

To overcome these challenges and realize the full potential of innovative and sustainable food technologies, a multipronged approach is needed.

Research and development: It is essential to prioritize interdisciplinary research that integrates food science, biotechnology, and engineering. Innovations should focus on achieving a balance between sustainability, affordability, and health benefits. By fostering cross-disciplinary collaboration, it will be possible to develop novel food technologies that address both consumer needs and environmental challenges.

Regulatory and policy support: Clear, science-based regulations should be developed to support responsible innovation in the food sector. These regulations must ensure food safety while encouraging technological advancements. Additionally, providing incentives for sustainable practices and technologies will drive further development and adoption of environmentally friendly solutions within the food industry.

Public engagement and education: Raising public awareness about the benefits and safety of novel food technologies is crucial for fostering consumer trust. Transparency and education efforts should focus on demystifying these technologies, explaining their potential, and addressing any concerns. This engagement will help build confidence in new food products and ensure their acceptance.

Infrastructure and supply chain development: Investing in resilient and adaptable food supply chains is vital for accommodating future food production innovations. Supporting localized production models can help reduce food miles, enhance sustainability, and strengthen regional food security. A robust infrastructure will enable the efficient distribution of novel food products to consumers.

Economic and market strategies: Supporting startups and entrepreneurs in the food technology space is key to fostering innovation and economic growth. Creating inclusive markets that ensure access to sustainable foods across various socio-economic groups will promote equitable food systems, ensuring that everyone can benefit from advancements in food production technologies.

Collaboration and partnerships: Fostering collaboration among academia, industry, government, and consumers will accelerate the development and adoption of novel food technologies. Promoting global cooperation will allow for the sharing of knowledge, technologies, and best practices, helping to address common challenges and scale solutions for the future.

Conclusion

The intersection of innovation and sustainability becomes increasingly crucial to meeting global food demands responsibly. The integration of cutting-edge technologies, such as non-thermal preservation methods, alternative proteins, and 3D food printing, offers transformative solutions for producing food that is nutritious, safe, and environmentally friendly. However, the success of these innovations depends not only on technological advancement but also on the creation of supportive policies that promote equitable access, consumer acceptance, and regulatory clarity. To ensure successful adoption and scaling of these innovations, collaboration between researchers, industry leaders, policymakers, and consumers is essential. Through this collective effort, a food system that is resilient to climate change, reduces waste, enhances nutritional quality, and supports sustainable agricultural practices can be built. Furthermore, the pursuit of circular food systems, which valorize food waste and by-products, presents an opportunity to create a more efficient and sustainable food ecosystem.

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Eco-Ethics in Action: Building a Socially Conscious Foundation for Sustainable Development through Eco-Innovation in Business

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Abstract

This article explores the critical role of eco-ethics in advancing sustainable development through education, community engagement, and eco-innovation in business. Emphasising ethical decision-making as a foundation for future-oriented policies and practices, the paper examines how educational institutions, local communities, and industries can collaborate to address environmental challenges. Drawing from global examples and cultural traditions, particularly those rooted in Tamil and Eastern philosophies, it argues for an interdisciplinary and culturally inclusive approach to sustainability. The article also discusses the evolution of economic thinking towards green and circular models, and how eco-ethics can guide transitions in policy, production, and consumption. The conclusion reinforces that integrating ethics with innovation and collaboration offers a viable and hopeful path toward a just and sustainable future.

Introduction

The challenges posed by climate change, environmental degradation, and the depletion of natural resources compel a fundamental rethinking of how societies live, work, and conduct business. In this context, sustainable development is not a peripheral or aspirational goal—it is an urgent imperative. At the core of this transformation lies the principle of eco-ethics: a framework of values and responsibilities that guides decisions today in ways that safeguard ecological integrity for future generations.

Education is pivotal in cultivating this ethical consciousness. From early childhood, education must transcend the transmission of knowledge to instill a sense of stewardship for the natural world. Learning should foster ecological literacy—an understanding of how ecosystems function, the significance of biodiversity, and the consequences of environmental neglect. Experiential learning, such as school gardening or waste-reduction initiatives, reinforces these values by encouraging direct engagement with nature. At the tertiary level, universities have the potential to serve as incubators of eco-innovation. Through interdisciplinary collaboration and research, they can produce the scientific and technological solutions necessary to transition toward a sustainable economy. Partnerships between academia and industry are critical in accelerating the practical application of such innovations.

Community-level action forms another essential pillar. Local initiatives—whether reforestation, river clean-ups, or community gardens—not only enhance environmental quality but also foster a collective ethic of care. Civic engagement and participatory governance strengthen the legitimacy and effectiveness of environmental policies. Moreover, awareness campaigns, both traditional and digital, can empower citizens to make informed, responsible choices, especially when people are included in the processes that shape their environments.

Businesses, meanwhile, are uniquely positioned to drive systemic change through eco-innovation. Increasingly, firms are adopting practices that reduce environmental footprints: shifting to renewable energy, optimizing resource use, and designing sustainable products. Such approaches are often economically advantageous while simultaneously enhancing corporate reputation. Corporate social responsibility (CSR), when authentically embedded in core operations, reflects a deeper commitment to ethical and environmental accountability. True CSR requires more than symbolic gestures; it calls for sustainable sourcing, equitable labor practices, ethical investment strategies, and transparent impact assessment. Multi-sectoral collaborations—among businesses, academic institutions, and civil society—can catalyze broader transformations and scale up innovative solutions.

Nonetheless, significant ethical dilemmas persist. Some corporate actors prioritize profit over environmental responsibility, engaging in practices such as illegal deforestation, toxic dumping, or deceptive “greenwashing” campaigns. These behaviors undermine public trust and environmental progress. Similarly, governments may fall short, either through weak regulatory enforcement or a narrow focus on short-term economic growth. Structural issues such as corruption and bureaucratic inertia further obstruct meaningful reform. At the individual level, consumer culture, convenience-driven habits, and apathy contribute to the deepening crisis. Yet, these challenges are not undefeatable. With critical reflection and coordinated action, societies can shift towards more ethical and sustainable paradigms.

There are encouraging global precedents. Sweden’s integration of circular economy principles, high recycling rates, and investments in renewable energy exemplify what a coherent, long-term strategy can achieve. Costa Rica has demonstrated that strong conservation policies and a national commitment to carbon neutrality can coexist with economic development. Such examples affirm that sustainability is both possible and practical.

The field of economics itself is undergoing a transformation. Concepts like the green economy and circular economy challenge conventional models by reframing the environment as a foundational partner in development. These frameworks promote regenerative design, long-term efficiency, and systems thinking—offering a compelling alternative to the extractive "take-make-dispose" model that has dominated industrial production for decades.

Cultural traditions also offer rich reservoirs of ecological wisdom. Tamil agricultural practices historically valued harmony with land, water, and animals. Rituals and festivals such as *Pongal* express gratitude to nature, reinforcing an ethic of reciprocity and care. Broader Eastern philosophies—from Hinduism and Buddhism to Jainism—highlight principles of interconnectedness, balance, and non-violence. These perspectives challenge Western individualism and anthropocentrism, offering insights that are particularly relevant in the face of ecological crisis. The future of sustainability may well depend on our capacity to integrate such cultural and philosophical diversity into global environmental discourse.

A just and sustainable future demands interdisciplinarity. The social sciences illuminate behavioral change, governance mechanisms, and social justice. The humanities provide critical ethical perspectives, historical context, and moral imagination. The natural sciences supply empirical knowledge, models, and technological tools. Only by fostering collaboration across these fields—economists, environmentalists, artists, philosophers, and activists—can society develop comprehensive, context-sensitive solutions. Whether addressing waste management, renewable infrastructure, or climate adaptation, the complexity of the environmental crisis necessitates multifaceted approaches.

Conclusion

In conclusion, eco-ethics must become the guiding compass of development. It is not merely a theoretical ideal but a practical foundation for policymaking, education, innovation, and enterprise. If societies are to meet the needs of the present without compromising the future, ethical reasoning must inform every level of decision-making—from individual consumption to global governance. By rooting our collective actions in principles of justice, care, and responsibility, and by embracing cross-disciplinary and cross-cultural collaboration, we can move toward a model of development that honors both people and planet. The path forward is not only possible—it is essential.

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