ISBN: 978-93-48620-17-0

Science and Technology for Sustainable Future Volume II

Editors:

Dr. Alok Ranjan Sahu
Dr. Dharna Bisen
Mr. Narinder Kumar
Dr. Umesh Sankpal

Bhumi Publishing, India
First Edition: May 2025

Science and Technology for Sustainable Future Volume II

(ISBN: 978-93-48620-17-0)

Editors

Dr. Alok Ranjan Sahu

Department of Botany,

Vikash Degree College,

Bargarh, Odisha

Dr. Dharna Bisen

Department of Entomology,

Raja Bhoj College of Agriculture,

Balaghat, JNKVV, Jabalpur, M.P.

Mr. Narinder Kumar

Department of Physics,

Guru Kashi University,

Talwandi Sabo, Bathinda, Punjab

Dr. Umesh Sankpal

Department of Chemistry,

Gogate – Jogalekar College,

Ratnagiri, Maharashtra

Bhumi Publishing

May 2025

Title: Science and Technology for Sustainable Future Volume II

Editors: Dr. Alok Ranjan Sahu, Dr. Dharna Bisen, Mr. Narinder Kumar, Dr. Umesh Sankpal

First Edition: May 2025

ISBN: 978-93-48620-17-0

Published by:

Bhumi Publishing

BHUMI PUBLISHING

Nigave Khalasa, Tal – Karveer, Dist – Kolhapur, Maharashtra, INDIA 416 207

E-mail: **bhumipublishing@gmail.com**

PREFACE

The dawn of the 21st century has heralded unprecedented advancements in science and technology, reshaping every aspect of human life. From communication and healthcare to agriculture and energy, scientific innovations are propelling society forward at an astonishing pace. Yet, amid this rapid progress lies an urgent and overarching challenge—the need for sustainability. As the global population grows and natural resources dwindle, the imperative to develop sustainable solutions through science and technology has never been more critical.

This book, Science and Technology for Sustainable Future, is a comprehensive collection of insights, research findings, and innovative approaches aimed at promoting sustainable development across diverse sectors. It brings together the work of scholars, researchers, and professionals who share a common vision: to harness the power of science and technology for the well-being of current and future generations.

The chapters in this volume explore a wide array of themes, including renewable energy technologies, sustainable agriculture, environmental conservation, green chemistry, climate change mitigation, and smart infrastructure. By highlighting both theoretical advancements and practical implementations, this book seeks to bridge the gap between research and real-world application, inspiring new solutions to pressing global challenges.

Our objective in compiling this volume is not only to share knowledge but also to stimulate dialogue, collaboration, and action among academicians, policymakers, industry leaders, and students. It is our hope that this book will serve as a valuable resource and a catalyst for innovation in building a more equitable, resilient, and sustainable world.

We extend our sincere gratitude to all the contributors for their scholarly work and to the editorial team for their dedication and commitment to this project. Together, we embark on a journey toward a sustainable future—guided by science, driven by innovation, and grounded in a deep responsibility to our planet and its people.

- Editors

TABLE OF CONTENT

COMPOSITE MATERIALS IN AGRICULTURE: A BRIEF INSIGHT INTO SUSTAINABLE SOLUTIONS

Himanshu Sharma and Nisha Sharma*

Department of Chemistry, Himachal Pradesh University, Shimla -171005, India

*Corresponding author E-mail: nishachemhpu@gmail.com

Abstract:

Plants can be cultivated not only in soil but also in soil-less environments, such as hydroponics, aeroponics, and aquaponics. These plants, just like those in traditional soil cultivation, require a balanced supply of macronutrients and micronutrients to support their growth. Nutrient deficiencies often lead to stunted growth, decreased yield potential, and physiological deformities in the plants. To overcome nutrient deficiencies and promote healthy plant growth, chemical fertilizers are commonly utilized in agriculture. However, the indiscriminate use of these fertilizers poses environmental challenges as the excess nutrients can leach into water sources and degrade soil quality over time. To address these issues, the development of composite materials has emerged as a promising solution in modern agriculture. By incorporating advanced materials into nutrient formulations, composite fertilizers are designed to exhibit controlled and prolonged release properties, ensuring a steady supply of nutrients to the crops with less risk of nutrient leaching. These composite materials form the basis of Slow-release fertilizers (SRF) and Controlled release fertilizers (CRF), which offer sustained nutrient release over time, thus optimizing nutrient availability and minimizing losses. The structural and compositional properties of these composites largely govern the nutrient release kinetics in both aqueous and soil systems. Through careful experimentation and release modeling, these fertilizers can be tailored to specific crop and environmental needs, leading to enhanced agricultural productivity and sustainable development.

Keywords: Fertilizers, Macro and Micro Nutrients, Composite Materials, Sustainable Agriculture.

Introduction:

Agriculture is considered as one the most important sector and plays a pivotal role in the socio-economic development of any nation. Beyond food production, it also contributes significantly to GDP, economic growth, ensures food security, supports rural development, social stability and provides raw materials for inductries (Cervantes-Godoy *et al.*, 2010; Jones *et al.*, 2016). Traditionally, soil has been the medium for crop cultivation and itself provide a variety of nutrients essential for plant growth (Powlson *et al.*, 2011). Different soil types, such as loamy, clayey, sandy, and silt contain different nutrients and thus support the growth of diverse crops (Winch *et al.*, 2006). However, innovations in agriculture have led to alternative cultivation methods that do not rely on soil and are represented in Fig.1.

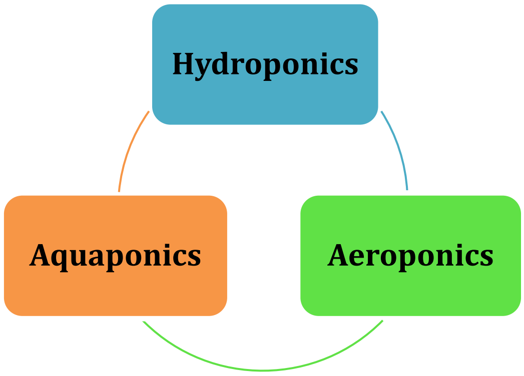

Fig. 1: Different techniques used for crop growth without soil

Hydroponics

Hydroponics is a soil-less technique where crops are grown in water enriched with nutrients. It offers advantages such as requirement of limited space, less labor and prevention of soil borne plant diseases (Gaikwad *et al.*, 2020). Crops like red onion (Rahmat *et al.*, 2019), garlic (Tambogon *et al.*, 2022), ginger (Rafie *et al.*, 2003), mint (Janpen *et al.*, 2019) and potatoes (Chang *et al.*, 2012) have been successfully grown hydroponically.

Aeroponics

The roots are suspended in air and periodically sprayed with nutrient-rich solutions. The plant roots hang in the artificial holder and foam material-based replacement of the soil are used under controlled conditions. The suspended roots in the air are periodically sprayed with nutrient-rich solutions to ensure proper nutrient supply to the crop (Lakhiar *et al.*, 2017; Lakhiar *et al.*, 2020). Crops such as potato, yams, tomatoes, and leafy vegetables have shown good adaptability to this method (Farran *et al.*, 2006; Gopinath *et al.*, 2017; Boddu *et al.*, 2024).

Aquaponics

Aquaponics integrates aquaculture with hydroponics in a closed-loop system. It is highly efficient, uses less water than traditional farming methods in which waste produced by fish is converted by beneficial bacteria into nutrients that can be absorbed by plants, which in turn purify the water for the fish, and creates healthy environment. This system is resource-efficient and eliminates the need for synthetic fertilizers (Yep *et al.*, 2019). Crops like lettuce, basil, okra and many other crops have thrived in aquaponics effectively (Bailey *et al.*, 2017).

Nutrient Requirements for Plant growth

In all mediums plants require both macro and micronutrients for optimum growth and overall development. Minerals such as N, P, K, Mg, Ca, S are called macronutrients because of their high quantity requirements and Fe, Cu, Zn, Mn, Mo, Ni required in low quantity are called micronutrients (Nadeem *et al.,* 2018; Fan *et al.,* 2021). Traditional fertilizers, such as NPK, urea and metal-based salts are widely used to supply these nutrients. Among these, urea and NPK, are mostly used as macronutrient supplier and metal salts fertilizers are used as micronutrient suppliers. Fertilizers ensure proper supply of nutrients which is useful in plant growth and its repair (Stewart *et al.,* 2012; Assefa *et al.,* 2019). Usually, the fertilizers are applied to the crop using foliar spray or directly into the soil (Fageria *et al.,* 2009).

However, excessive or improper application of fertilizers can reduce nutrient use efficiency, degrade soil health, and cause ecological damage (Rahman *et al.,* 2018; Lenka *et al.,* 2016). Further the runoff from such fertilizers can lead to water pollution, harming both terrestrial and aquatic ecosystems. Therefore, to prevent the harmful effects caused due to fast release of nutrients from conventional fertilizer slow and controlled release fertilizer can be a better option which restricts the release rate of nutrient and thereby decreases pollution and helps in sustainable development (Wei *et al.,* 2020).

Composites as Slow and Controlled Release Fertilizers

Composite materials are engineered by combining two or more constituents to produce superior properties compared to the individual components. These composites, usually consisting of a matrix and active ingredients, are effective and have applications in various fields such as agriculture, antimicrobials, pharmaceuticals, wastewater treatment and catalysis (Firmanda *et al.,* 2022). In agriculture, composites are used to develop slow (SRFs) as well as controlled release fertilizers (CRFs) which release the required nutrients in efficient ways, offering sustained nutrient availability and promoting environmental sustainability by reducing nutrient-based pollution (Sholeha *et al.,* 2024; Andelkovic *et al.,* 2018). Most important types of composites in agriculture includes-

1. Ceramic Matrix Composites (CMC)
2. Polymer Matrix Composites (PMC)

Ceramic composites are inorganic composites that can be crystalline or amorphous in nature. These are usually composed of metal oxides, nitrides and carbides their common examples contain clay, alumina, silica etc. Ceramic composites can be prepared from materials like hydroxyapatite, zeolite, bentonite, kaolinite and halloysite (Sogo *et al.,* 2004; Marocco *et al.,* 2012; Asal *et al.,* 2021; Sánchez-Soto *et al.,* 2022) These materials are able to incorporate a lot of nutrients and facilitating their slow and efficient release, which leads to better crop development (Sharma *et al.,* 2022; Khan *et al.,* 2021; Neto *et al.,* 2023).

Polymer composites mainly include organic composites that are designed to be used in crop production and consist of soluble nutrients as a core surrounded by a polymer. Polymeric composites contain branch of cross-linked hydrophilic polymers, which can retain water in the swollen state and release of nutrients occurs by diffusion across a semipermeable membrane.

Polyethylene, polypropylene, polyurethane, and polystyrene are the most used hydrophobic polymers, while hydrophilic polymer like polyacrylic acid (PAA) act as superabsorbent (Abd El-Aziz *et al.*, 2022). Nutrients doping to the polymer can results in formation of slow and controlled release fertilizers (Sharma *et al.*, 2019; Magaletti *et al.*, 2023). Further, some additional materials such as chitosan and biochar are also explored for agricultural composites (Hernández-Téllez *et al.*, 2016; Wang *et al.*, 2022). The effectiveness of a composite as a fertilizer usually depends on its composition. A number of composite based fertilizers having different compositions and slow release of nutrients have already been developed and tested in water and soil. Some of these studies are shown in Table 1.

Table 1: Composition, slow-release efficiency and growth testing of various composites

Composition of fertilizer	**Slow-release efficiency**	**Testing on crop**	**Reference**
Hydroxyapatite, copper, iron, zinc and urea	Effective slow release of nutrients for 14 days	Produced better growth on (*Abelmoschus esculentus*) plant	Tarafder *et al.*, 2020
Hydroxyapatite and urea	Slow release of N for 1 week	Reduces urea requirement and produced better rice crops than control	Kottegoda *et al.*, 2017
Nano Zeolite and urea	Slow release of N upto 48 days	-	Manikandan *et al.*, 2013
Bentonite and saxan	-	Tested on corn and showed better overall growth of the plant	Tian *et al.*, 2024
Biochar, (Fertilizer granules K_2O, P_2O_5, N)	Slow release of N was witnessed for 84 days	Showed effective results in paddy field	Dong et al. 2020
Polyurethane and urea	Controlled release of N for 20 hours	-	Sitthisuwannakul *et al.*, 2023
Carrageenan hydrogels and zinc	Slow and effective release for 14 days	Enhanced growth of wheatgrass in pot studies	Akalin *et al.*, 2020

Composite Synthesis and Characterization

A number of techniques have been used to synthesize composites and the nature of technique used depends upon the type of composite material. Some of the specific techniques used for composite synthesis are-

1. **Melt Mixing:** This technique involves thermal mixing and blending of polymer matrices with various reinforcing materials to produce composite materials (Parida *et al.*, 2024). Mostly used for synthesis of polymer-based composites and is effective in producing a large number of composites in a simple and cost-effective way (Banerjee *et al.,* 2019; Eskin *et al.,* 2003).
2. **Solution mixing:** This technique involves mixing of solutions of both matrix and reinforcing materials and allows high degree of dispersion of reinforcing materials into the matrix. This technique allows intimate mixing at molecular level and thus creates more uniform distributions. (Alver *et al.,* 2014; Kuila *et al.,* 2011).
3. **Compression Molding:** This technique involves applying heat and pressure to blend matrix and reinforcing materials into a mold. This technique is not much used for fertilizer based composite synthesis (Sreekumar *et al.,* 2007).
4. **Layer by layer assembly:** This technique utilizes alternating layers of matrix and reinforcing materials enabling precise structural control (Lee *et al.,* 2015).

Among these techniques solution mixing is mostly used in preparations of agriculture composites (Zhou *et al.,* 2018).

Characterization Techniques

Characterization of composites prepared for agricultural applications are done by techniques like XRD, FT-IR, SEM, TEM, EDS and elemental mapping. XRD refers to as X-ray diffraction and is used to determine crystalline and amorphous surface of the prepared composite (Ammar *et al.,* 2024). FT-IR (Fourier transform infrared spectroscopy) shows functional groups present in the composite material. SEM (Scanning electron microscopy) is used to judge the surface morphology of the prepared composite whereas TEM (Transmission electron microscopy) is used to judge internal morphology of prepared composite. EDS and elemental mapping reveal the elemental composition and position of elements in the composite (Wei *et al.,* 2019).

Release Behavior and Kinetics of Nutrients from Composite

Composite material based fertilizers show a slow and controlled release behaviour with a delayed and sustained nutrient release compared to traditional fertilizers, reducing the risk of leaching. Direct use of macro and micronutrient fertilizers leads to quick environmental release and causes environmental contamination. On the other hand, when nutrients are doped with advanced materials like hydroxyapatite, zeolite, chitosan, poly-urethane, bentonite and hydrogels they can show prolonged release of nutrients for large duration and often shows a sigmoidal release curve (Shaviv *et al.,* 2003) Fig. 2.

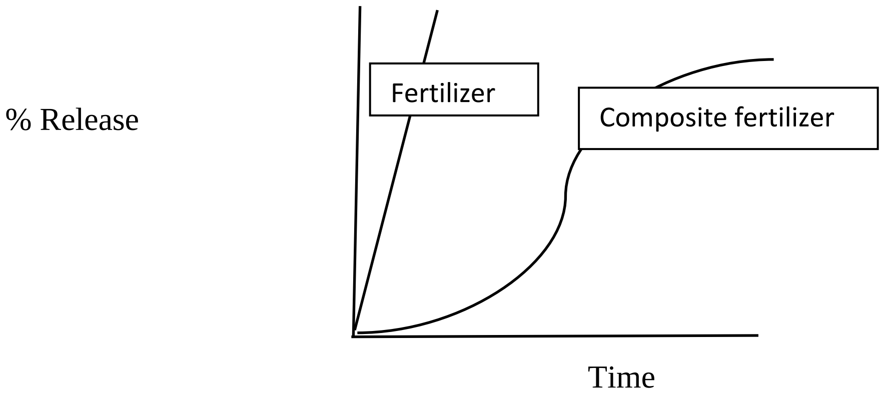

Fig. 2: Release of nutrients from fertilizer and composite based fertilizer

To understand the release kinetics of various fertilizers, different release models can be applied such as Zero order, First order, Higuchi and Korsmeyer-Peppas models. The applicability of these models can be judged by measuring the value of R^2, which helps to determine the most appropriate model for nutrient release behavior. The eqautions of different models are represented as-

Zero order kinetic model - $\frac{Ct}{C\infty} = k_0 t$

Higuchi model - $\frac{Ct}{C\infty} = K_H t^{1/2}$

Korsmeyer-Peppas model - $\frac{Ct}{C\infty} = K_{KP} t^n$

First order kinetic model - $\frac{Ct}{C\infty} = 1 - e^{-K1t}$

If release of nutrients from composite is independent to the nutrient concentration the composite follows zero order kinetic model. If release rate of nutrients decreases with decrease in amount of nutrient in the composite it follows first order kinetics. When the release of nutrients from the composite are driven by diffusion the composite follows Hugichi model (Sultan *et al.,* 2024). While Korsmeyer-Peppas model describe nutrient release from composite when the release mechanism is complex.

Conclusion and Future Challenges

Agriculture remains essential for national development, food security, and economic stability. While modern techniques like hydroponics, aeroponics and aquaponics are expanding the scope of cultivation, environmental challenges posed by conventional fertilizers necessitate the development of sustainable alternatives. In this direction, composite-based SRFs and CRFs, including ceramic and polymer composites, offer efficient nutrient release, enhances crop sustainability and reduce environmental impact. But the production of composites based slow-release fertilizer on a large scale is complex due to the problems involved in ensuring the proper formulation of nutrients, as well as the testing and quality control measures required to meet industry standards. In addition, the sourcing of raw materials at the necessary quantities adds another layer of difficulty to the production process. Despite these challenges and complexities involved, continued research and innovation in composite technology will be key to addressing future agricultural, environmental challenges and will help in sustainable agriculture practices.

References:

1. Abd El-Aziz, M. E., Salama, D. M., Morsi, S. M., Youssef, A. M., & El-Sakhawy, M. (2022). Development of polymer composites and encapsulation technology for slow-release fertilizers. *Reviews in Chemical Engineering*, *38*(5), 603-616. https://doi.org/10.1515/revce-2020-0044
2. Akalin, G. O., & Pulat, M. (2020). Controlled release behavior of zinc-loaded carboxymethyl cellulose and carrageenan hydrogels and their effects on wheatgrass growth. *Journal of Polymer Research*, *27*(1), 6. https://doi.org/10.1007/s10965-019-1950-y
3. Alver, E., Metin, A. Ü., & Çiftçi, H. (2014). Synthesis and characterization of chitosan/polyvinylpyrrolidone/zeolite composite by solution blending method. *Journal of Inorganic and Organometallic Polymers and Materials*, *24*, 1048-1054. https://doi.org/10.1007/s10904-014-0087-z
4. Ammar, M., Bortoletto-Santos, R., Ribeiro, C., Zhang, L., & Baltrusaitis, J. (2024). Mechanochemical synthesis of zinc-doped hydroxyapatite for tunable micronutrient release. *RSC Mechanochemistry*, *1*(3), 263-278. https://doi.org/10.1039/D3MR00012E
5. Andelkovic, I. B., Kabiri, S., Tavakkoli, E., Kirby, J. K., McLaughlin, M. J., & Losic, D. (2018). Graphene oxide-Fe (III) composite containing phosphate–A novel slow release fertilizer for improved agriculture management. *Journal of cleaner production*, *185*, 97-104. https://doi.org/10.1016/j.jclepro.2018.03.050
6. Asal, S., Erenturk, S. A., & Haciyakupoglu, S. (2021). Bentonite based ceramic materials from a perspective of gamma-ray shielding: Preparation, characterization and performance evaluation. *Nuclear Engineering and Technology*, *53*(5), 1634-1641. https://doi.org/10.1016/j.net.2020.11.009
7. Assefa, S., & Tadesse, S. (2019). The principal role of organic fertilizer on soil properties and agricultural productivity-a review. *Agric. Res. Technol. Open Access J*, *22*(2), 1-5. http://dx.doi.org/10.19080/ARTOAJ.2019.22.556192
8. Bailey, D. S., & Ferrarezi, R. S. (2017). Valuation of vegetable crops produced in the UVI Commercial Aquaponic System. *Aquaculture Reports*, *7*, 77-82. https://doi.org/10.1016/j.aqrep.2017.06.002
9. Banerjee, J., & Dutta, K. (2019). Melt-mixed carbon nanotubes/polymer nanocomposites. *Polymer Composites*, *40*(12), 4473-4488. https://doi.org/10.1002/pc.25334
10. Boddu, V., Ch, D. H. K., Sai Kumar, N., Bindiya, Y., & Rajani, A. (2024). Aeroponics in Vegetable Crops. *International Journal of Theoretical & Applied Sciences*, *16*(1), 74-78.

11. Cervantes-Godoy, D. and J. Dewbre (2010), "Economic Importance of Agriculture for Poverty Reduction", *OECD Food, Agriculture and Fisheries Papers*, No. 23, OECD Publishing, Paris, https://doi.org/10.1787/5kmmv9s20944-en.
12. Chang, D. C., Park, C. S., Kim, S. Y., & Lee, Y. B. (2012). Growth and tuberization of hydroponically grown potatoes. *Potato research*, *55*, 69-81. https://doi.org/10.1007/s11540-012-9208-7
13. Dong, D., Wang, C., Van Zwieten, L., Wang, H., Jiang, P., Zhou, M., & Wu, W. (2020). An effective biochar-based slow-release fertilizer for reducing nitrogen loss in paddy fields. *Journal of Soils and Sediments*, *20*, 3027-3040. https://doi.org/10.1007/s11368-019-02401-8
14. Eskin, G., & Eskin, D. G. (2003). Production of natural and synthesized aluminum-based composite materials with the aid of ultrasonic (cavitation) treatment of the melt. *Ultrasonics sonochemistry*, *10*(4-5), 297-301. https://doi.org/10.1016/S1350-4177(02)00158-X
15. Fageria, N. K., Filho, M. B., Moreira, A., & Guimarães, C. M. (2009). Foliar fertilization of crop plants. *Journal of plant nutrition*, *32*(6), 1044-1064. https://doi.org/10.1080/01904160902872826
16. Fan, X., Zhou, X., Chen, H., Tang, M., & Xie, X. (2021). Cross-talks between macro-and micronutrient uptake and signaling in plants. *Frontiers in Plant Science*, *12*, 663477. https://doi.org/10.3389/fpls.2021.663477
17. Farran, I., & Mingo-Castel, A. M. (2006). Potato minituber production using aeroponics: effect of plant density and harvesting intervals. *American Journal of Potato Research*, *83*, 47-53. https://doi.org/10.1007/BF02869609
18. Firmanda, A., Fahma, F., Syamsu, K., Suryanegara, L., & Wood, K. (2022). Controlled/slow-release fertilizer based on cellulose composite and its impact on sustainable agriculture. *Biofuels, Bioproducts and Biorefining*, *16*(6), 1909-1930. https://doi.org/10.1002/bbb.2433
19. Gaikwad, D. J., & Maitra, S. (2020). Hydroponics cultivation of crops. *Protected cultivation and smart agriculture*, *1*, 279-287. https://doi.org/10.30954/NDP-PCSA.2020.31
20. Gopinath, P., Vethamoni, P. I., & Gomathi, M. (2017). Aeroponics soilless cultivation system for vegetable crops. *Chemical Science Review and Letters*, *6*(22), 838-849.
21. Hernández-Téllez, C. N., Plascencia-Jatomea, M., & Cortez-Rocha, M. O. (2016). Chitosan-based bionanocomposites: development and perspectives in food and agricultural applications. *Chitosan in the preservation of agricultural commodities*, 315-338. https://doi.org/10.1016/B978-0-12-802735-6.00012-4

22. Janpen, C., Kanthawang, N., Inkham, C., Tsan, F. Y., & Sommano, S. R. (2019). Physiological responses of hydroponically-grown Japanese mint under nutrient deficiency. *PeerJ*, *7*, e7751. https://doi.org/10.7717/peerj.7751
23. Jones, A. D., & Ejeta, G. (2016). A new global agenda for nutrition and health: the importance of agriculture and food systems. *Bulletin of the World Health Organization*, *94*(3), 228. https://doi.org/10.2471/BLT.15.164509
24. Khan, M. Z. H., Islam, M. R., Nahar, N., Al-Mamun, M. R., Khan, M. A. S., & Matin, M. A. (2021). Synthesis and characterization of nanozeolite based composite fertilizer for sustainable release and use efficiency of nutrients. *Heliyon*, *7*(1). https://doi.org/10.1016/j.heliyon.2021.e06091
25. Kottegoda, N., Sandaruwan, C., Priyadarshana, G., Siriwardhana, A., Rathnayake, U. A., Berugoda Arachchige, D. M., ... & Amaratunga, G. A. (2017). Urea-hydroxyapatite nanohybrids for slow release of nitrogen. *ACS nano*, *11*(2), 1214-1221. https://doi.org/10.1021/acsnano.6b07781
26. Kuila, T., Bose, S., Hong, C. E., Uddin, M. E., Khanra, P., Kim, N. H., & Lee, J. H. (2011). Preparation of functionalized graphene/linear low density polyethylene composites by a solution mixing method. *Carbon*, *49*(3), 1033-1037. https://doi.org/10.1016/j.carbon.2010.10.031
27. Lakhiar, I. A., Gao, J., Syed, T. N., Chandio, F. A., & Buttar, N. A. (2018). Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. *Journal of plant interactions*, *13*(1), 338-352. https://doi.org/10.1080/17429145.2018.1472308
28. Lakhiar, I. A., Gao, J., Syed, T. N., Chandio, F. A., Tunio, M. H., Ahmad, F., & Solangi, K. A. (2020). Overview of the aeroponic agriculture–An emerging technology for global food security. *International Journal of Agricultural and Biological Engineering*, *13*(1), 1-10. https://dx.doi.org/10.25165/j.ijabe.20201301.5156
29. Lee, T., Min, S. H., Gu, M., Jung, Y. K., Lee, W., Lee, J. U., ... & Kim, B. S. (2015). Layer-by-layer assembly for graphene-based multilayer nanocomposites: synthesis and applications. *Chemistry of Materials*, *27*(11), 3785-3796. https://doi.org/10.1021/acs.chemmater.5b00491
30. Lenka, S., Rajendiran, S., Coumar, M. V., Dotaniya, M. L., & Saha, J. K. (2016, February). Impacts of fertilizers use on environmental quality. In *National seminar on environmental concern for fertilizer usein future at Bidhan Chandra KrishiViswavidyalaya, Kalyani on February* (Vol. 26, p. 2016).

31. Magaletti, R., Pizzetti, F., Masi, M., & Rossi, F. (2023). Biobased Materials as Promising Tools for the Slow-Release of Urea. *ACS Agricultural Science & Technology*, *3*(11), 957-969. https://doi.org/10.1021/acsagscitech.3c00450
32. Manikandan, A., & Subramanian, K. S. (2014). Fabrication and characterisation of nanoporous zeolite based N fertilizer. *Afr J Agric Res*, *9*(2), 276-284. https://doi.org/10.5897/AJAR2013.8236
33. Marocco, A., Dell'Agli, G., Esposito, S., & Pansini, M. (2012). Metal-ceramic composite materials from zeolite precursor. *Solid state sciences*, *14*(3), 394-400. https://doi.org/10.1016/j.solidstatesciences.2012.01.006
34. Nadeem, F., Hanif, M. A., Majeed, M. I., & Mushtaq, Z. (2018). Role of macronutrients and micronutrients in the growth and development of plants and prevention of deleterious plant diseases-a comprehensive review. *International Journal of Chemical and Biochemical Sciences*, *13*, 31-52.
35. Neto, J. F. D., Fernandes, J. V., Rodrigues, A. M., Menezes, R. R., & Neves, G. D. A. (2023). New urea controlled-release fertilizers based on bentonite and carnauba wax. *Sustainability*, *15*(7), 6002. https://doi.org/10.3390/su15076002
36. Parida, S. K., Kullu, S., Hota, S., & Mishra, S. (2024). Synthesis and processing techniques of polymer composites. In *Polymer Composites: Fundamentals and Applications* (pp. 39-66). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-2075-0_2
37. Powlson, D. S., Gregory, P. J., Whalley, W. R., Quinton, J. N., Hopkins, D. W., Whitmore, A. P., ... & Goulding, K. W. (2011). Soil management in relation to sustainable agriculture and ecosystem services. *Food policy*, *36*, S72-S87.
38. Rafie, A. R., Olczyk, T., & Guerrero, W. (2003, December). Hydroponic production of fresh ginger roots (Zingiber officinale) as an alternative method for South Florida. In *Proceedings of the Florida State Horticultural Society* (Vol. 116, pp. 51-52).
39. Rahman, K. A., & Zhang, D. (2018). Effects of fertilizer broadcasting on the excessive use of inorganic fertilizers and environmental sustainability. *Sustainability*, *10*(3), 759. https://doi.org/10.3390/su10030759
40. Rahmat, R. F., Adnan, S., Anugrahwaty, R., Alami, E. P. S., & Siregar, B. (2019, June). Red onion growth monitoring system in hydroponics environment. In *Journal of Physics: Conference Series* (Vol. 1235, No. 1, p. 012117). IOP Publishing. 10.1088/1742-6596/1235/1/012117
41. Sánchez-Soto, P. J., Eliche-Quesada, D., Martínez-Martínez, S., Pérez-Villarejo, L., & Garzón, E. (2022). Study of a waste kaolin as raw material for mullite ceramics and mullite refractories by reaction sintering. *Materials*, *15*(2), 583. https://doi.org/10.3390/ma15020583

42. Sharma, B., Afonso, L. O., Singh, M. P., Soni, U., & Cahill, D. M. (2022). Zinc-and magnesium-doped hydroxyapatite-urea nanohybrids enhance wheat growth and nitrogen uptake. *Scientific Reports*, *12*(1), 19506. https://doi.org/10.1038/s41598-022-20772-w
43. Sharma, N., & Singh, A. (2019). A review on changes in fertilizers: from coated controlled release fertilizers (CRFs) to nanocomposites of CRFs. *Int. J. Agric. Sci. Res*, *9*(2), 53-74.
44. Shaviv, A., Raban, S., & Zaidel, E. (2003). Modeling controlled nutrient release from polymer coated fertilizers: Diffusion release from single granules. *Environmental science & technology*, *37*(10), 2251-2256. https://doi.org/10.1021/es011462v
45. Sholeha, N. A., Wiraguna, E., Urip, T., Sujarnoko, P., & Budiono, D. (2024). Fabrication and Effectiveness of Composite Materials in Urea Slow-Release Fertilizers: A Mini-Review. *Biointerface Research in Applied Chemistry*, *14*(5), 1-20. https://doi.org/10.33263/BRIAC145.112
46. Sitthisuwannakul, K., Boonpavanitchakul, K., Wirunmongkol, T., Muthitamongkol, P., & Kangwansupamonkon, W. (2023). A tunable controlled-release urea fertilizer coated with a biodegradable polyurethane-nanoclay composite layer. *Journal of Coatings Technology and Research*, *20*(2), 635-646. https://doi.org/10.1007/s11998-022-00688-w
47. Sogo, Y., Ito, A., Fukasawa, K., Sakurai, T., & Ichinose, N. (2004). Zinc containing hydroxyapatite ceramics to promote osteoblastic cell activity. *Materials science and technology*, *20*(9), 1079-1083. https://doi.org/10.1179/026708304225019704
48. Sreekumar, P. A., Joseph, K., Unnikrishnan, G., & Thomas, S. (2007). A comparative study on mechanical properties of sisal-leaf fibre-reinforced polyester composites prepared by resin transfer and compression moulding techniques. *Composites science and technology*, *67*(3-4), 453-461. https://doi.org/10.1016/j.compscitech.2006.08.025
49. Stewart, W. M., & Roberts, T. L. (2012). Food security and the role of fertilizer in supporting it. *Procedia Engineering*, *46*, 76-82. https://doi.org/10.1016/j.proeng.2012.09.448
50. Sultan, M., & Taha, G. (2024). Sustained-release nitrogen fertilizer delivery systems based on carboxymethyl cellulose-grafted polyacrylamide: Swelling and release kinetics. *International Journal of Biological Macromolecules*, *266*, 131184. https://doi.org/10.1016/j.ijbiomac.2024.131184
51. Tambogon, D. R. A., & Yumang, A. N. (2022, March). Growth of Garlic in Hydroponic System with IoT-Based Monitoring. In *2022 14th International Conference on Computer and Automation Engineering (ICCAE)* (pp. 184-189). IEEE. https://doi.org/10.1109/ICCAE55086.2022.9762436
52. Tarafder, C., Daizy, M., Alam, M. M., Ali, M. R., Islam, M. J., Islam, R., ... & Khan, M. Z. H. (2020). Formulation of a hybrid nanofertilizer for slow and sustainable release of

micronutrients. *ACS omega*, *5*(37), 23960-23966. https://doi.org/10.1021/acsomega.0c03233

53. Tian, T., Li, X., Jia, Y., Li, K., Hou, X., Zhao, F., & Huang, H. (2024). Bentonite-enhanced sanxan: A pathway to slow-release, eco-friendly fertilizers. *Journal of Cleaner Production*, *485*, 144396. https://doi.org/10.1016/j.jclepro.2024.144396
54. Wang, C., Luo, D., Zhang, X., Huang, R., Cao, Y., Liu, G., ... & Wang, H. (2022). Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review. *Environmental Science and Ecotechnology*, *10*, 100167. https://doi.org/10.1016/j.ese.2022.100167
55. Wei, H., Wang, H., Chu, H., & Li, J. (2019). Preparation and characterization of slow-release and water-retention fertilizer based on starch and halloysite. *International journal of biological macromolecules*, *133*, 1210-1218. https://doi.org/10.1016/j.ijbiomac.2019.04.183
56. Wei, X., Chen, J., Gao, B., & Wang, Z. (2020). Role of controlled and slow release fertilizers in fruit crop nutrition. In *Fruit crops* (pp. 555-566). Elsevier. https://doi.org/10.1016/B978-0-12-818732-6.00039-3
57. Winch, T. (2006). Section 1 The principles and practices used in agriculture and horticulture. *Growing Food: A Guide to Food Production*, 1-103. https://doi.org/10.1007/978-1-4020-4975-0_1
58. Yep, B., & Zheng, Y. (2019). Aquaponic trends and challenges–A review. *Journal of Cleaner Production*, *228*, 1586-1599. https://doi.org/10.1016/j.jclepro.2019.04.290
59. Zhou, T., Wang, Y., Huang, S., & Zhao, Y. (2018). Synthesis composite hydrogels from inorganic-organic hybrids based on leftover rice for environment-friendly controlled-release urea fertilizers. *Science of the Total Environment*, *615*, 422-430. https://doi.org/10.1016/j.scitotenv.2017.09.084

CARBON FARMING: ECONOMIC IMPLICATIONS AND OPPORTUNITIES FOR SUSTAINABLE AGRICULTURAL DIVERSIFICATION

Shivam Srivastav[1], Harshit Mishra*[2],
Deep Chand Nishad[3], Kartikay Srivastava[4] and Sandeep Kumar[5]

[1]Department of Genetics and Plant Breeding, Bihari Lal Smarak Kisan P. G. College, Amadarveshpur, Ambedkar Nagar (U.P.) – 224 139,
Affiliated to Dr. Rammanohar Lohia Avadh University Ayodhya, U.P.

[2]Department of Agricultural Economics, College of Agriculture, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh – 224 229

[3]Department of Agronomy, Shri Durga Ji Post Graduate College, Chandeshwar, Azamgarh 276 128, Affiliated to Veer Bahadur Singh Purvanchal University, Jaunpur, U.P.

[4]Department of Genetics and Plant Breeding, Shri Durga Ji Post Graduate College, Chandeshwar, Azamgarh (U.P.) – 276 128,
Affiliated to Veer Bahadur Singh Purvanchal University, Jaunpur, U.P.

[5]Department of Agronomy, Shri Durga Ji Post Graduate College, Chandeshwar, Azamgarh, 276 128, Affiliated to Maharaja Suhel Dev University, Azamgarh, U.P.

*Corresponding author E-mail: wehars@gmail.com

Abstract:

Agriculture significantly contributes to greenhouse gas emissions, highlighting the urgent need for sustainable farming practices. This chapter explores how agricultural lands can mitigate emissions and enhance carbon sequestration. It examines carbon farming methods such as agroforestry, cover cropping, reduced tillage, livestock management, and organic farming, assessing their sequestration potential, economic viability, and implementation challenges. A detailed cost-benefit analysis considers investment requirements, long-term gains, and emerging opportunities in carbon markets, including offset programs and carbon trading that can offer farmers new income sources. Government policies and incentives are also reviewed for their role in promoting these practices. The chapter addresses key barriers—technical, economic, and regulatory—and proposes strategies for wider adoption, including farmer education, financial support, and policy reform. Future prospects are considered through the lens of technological advancements, global market dynamics, and carbon farming's role in enhancing climate and economic resilience. Ultimately, the chapter positions carbon farming as a viable solution for aligning environmental sustainability with agricultural profitability, paving the way for a climate-resilient and economically sustainable agricultural future.

Keywords: Agricultural Diversification, Carbon Farming, Climate Mitigation, Economic Implications, Sustainable Agriculture

1. Introduction:

Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020 (IPCC, 2023). The observed changes in global surface temperature from 1900 to 2020, as well as the projected changes from 2021 to 2100 relative to the period 1850-1900, provide insights into the evolving climate conditions and their impacts (Rosa- Schleich *et al.*, 2019; Tiwari *et al.*, 2011). These changes offer a glimpse into how the climate has transformed and will continue to do so over the lifespans of three representative generations: those born in 1950, 1980, and 2020. Future projections for the period 2021-2100 depict variations in global surface temperature based on different greenhouse gas emissions scenarios. These scenarios range from very low (SSP1-1.9) to very high (SSP5-8.5) emissions scenarios (Bowman and Zilberman, 2013).

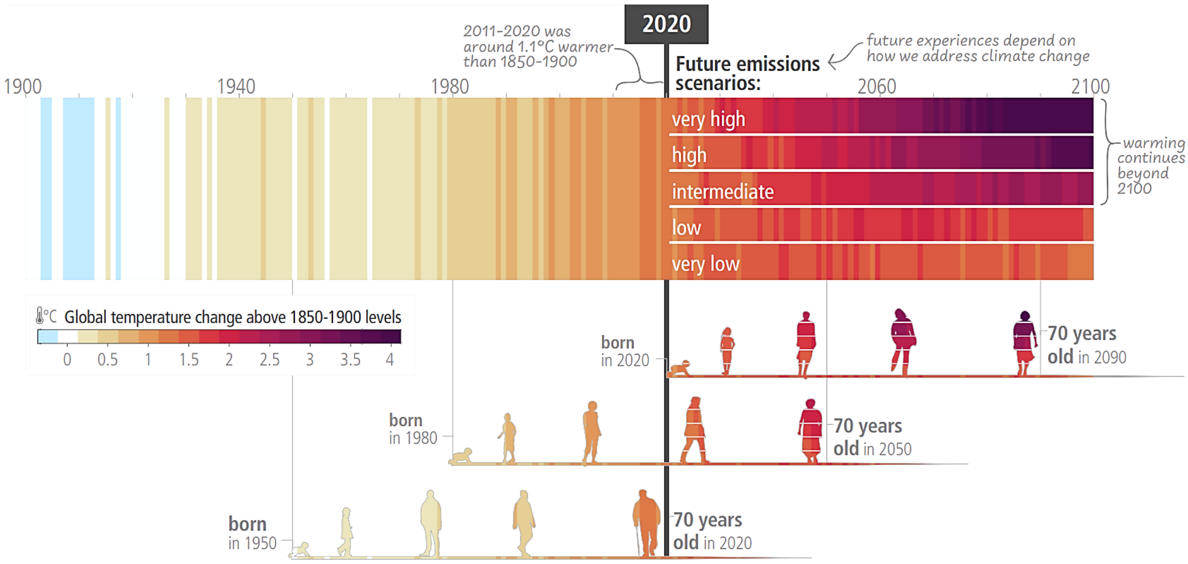

Fig. 1: Observed (1900-2020) and projected (2021–2100) changes in global surface temperature (IPCC, 2023)

These temperature changes are visually represented using ‘climate stripes,’ which illustrate the long-term trends influenced by human activities and the ongoing natural variability, as indicated by past observations. In this representation, the colours on generational icons correspond to the global surface temperature stripes for each year, and segments on future icons differentiate the potential climate experiences that these generations may encounter (Cusworth *et al.*, 2021; Mishra and Mishra, 2025). This visualization effectively communicates the historical and projected shifts in global surface temperature and underscores the importance of addressing greenhouse gas emissions to mitigate future climate impacts (IPCC, 2023).

Agriculture, as both a primary source of sustenance and a major contributor to global greenhouse gas emissions, occupies a critical position in the discourse surrounding climate change mitigation. In recent years, the concept of “Carbon Farming” has emerged as a promising strategy to address the dual challenge of enhancing agricultural productivity while simultaneously reducing its carbon footprint (Hufnagel *et al.,* 2020). By exploring the multifaceted aspects of Carbon Farming, it seeks to unravel the economic implications and opportunities associated with its adoption in the context of sustainable agricultural diversification. Carbon Farming, at its core, represents a paradigm shift in the way we view agriculture's role in climate change mitigation. It encompasses a diverse range of practices and techniques aimed at sequestering carbon dioxide from the atmosphere and enhancing carbon storage in agricultural soils and vegetation (Adhikari *et al.,* 2023).

As such, the chapter commences by elucidating the pivotal role agriculture plays in climate change mitigation. It underscores the pressing need for innovative approaches to transform agriculture from a significant emitter to a vital carbon sink. In this context, Carbon Farming practices emerge as a beacon of hope, capable of reshaping the agricultural landscape while aligning with broader sustainability objectives (Tacconi *et al.,* 2022). The subsequent sections of this chapter explain the core components of Carbon Farming practices. These practices encompass a spectrum of techniques, from no-till farming and cover cropping to agroforestry and rotational grazing. Each practice is evaluated in terms of its effectiveness in sequestering carbon, improving soil health, and increasing overall farm resilience. Moreover, we explore the potential synergies and trade-offs between different Carbon Farming techniques, shedding light on the complexities faced by farmers and policymakers in adopting these practices (Yang *et al.,* 2014).

However, the transition to Carbon Farming is not without its economic implications and challenges. The chapter takes a critical view of the economic aspects, examining the costs and benefits associated with Carbon Farming adoption. It considers factors such as changes in input costs, yield variations, and market opportunities, aiming to provide a comprehensive understanding of the economic calculus faced by farmers. In doing so, it also highlights the potential for Carbon Farming to generate alternative revenue streams through carbon credits and ecosystem services (Kremen *et al.,* 2012). Nonetheless, Carbon Farming faces a host of challenges and barriers that must be overcome for widespread adoption. The chapter scrutinizes these obstacles, ranging from knowledge gaps and technical hurdles to policy uncertainties and market limitations. It underscores the need for a holistic approach that combines technological innovation, knowledge dissemination, and supportive policy frameworks to facilitate the mainstreaming of Carbon Farming practices (Liu *et al.,* 2016).

In response to these challenges, the chapter outlines strategies for promoting Carbon Farming adoption. It identifies major stakeholders and their roles in advancing this transformative agenda, emphasizing the importance of collaborative efforts among farmers, researchers, governments, and private sector actors. Furthermore, we underscore the role of education and outreach in bridging the information gap and fostering a culture of sustainable farming practices (Barnes *et al.,* 2022; Mishra *et al.,* 2025). Finally, we conclude by looking towards the future prospects and opportunities that Carbon Farming presents. It envisions a landscape where agriculture becomes a major player in mitigating climate change while concurrently bolstering food security and rural livelihoods. The potential for carbon markets, technological advancements, and international cooperation is explored as catalysts for realizing this vision.

2. The Role of Agriculture in Climate Change Mitigation

Agriculture, as one of the cornerstones of human civilization, plays a pivotal role in both contributing to and mitigating climate change. This section discusses the multifaceted relationship between agriculture and climate change, highlighting its impact on greenhouse gas emissions, its potential for carbon sequestration, and the pressing need for sustainable farming practices.

2.1 Agriculture's contribution to greenhouse gas emissions

Agriculture is a significant contributor to global greenhouse gas emissions. Various activities within the sector release carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), the three primary greenhouse gases responsible for global warming.

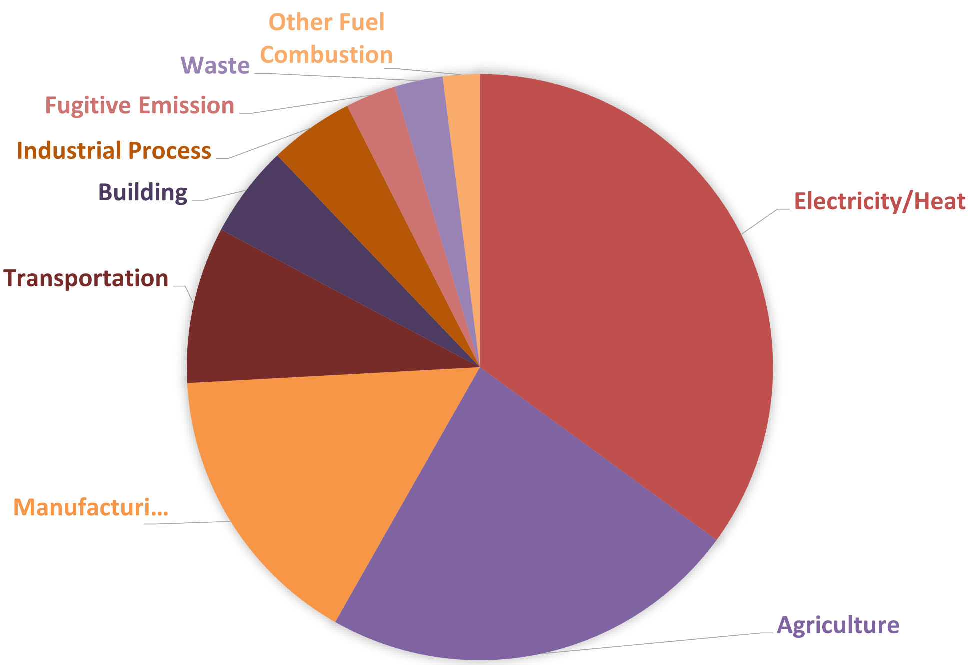

Fig. 2: Sector wise distribution of GHG emissions in India in 2020 (www.statista.com)

These emissions arise from several sources:

- **Enteric fermentation:** Livestock, particularly ruminants like cattle, emit methane during digestion, making livestock agriculture a major source of methane emissions.
- **Manure management:** Improper handling and disposal of livestock manure release methane and nitrous oxide into the atmosphere.

- **Energy use:** The agricultural sector relies on fossil fuels for machinery, transportation, and energy-intensive processes, contributing to CO_2 emissions.
- **Land use change:** Deforestation and conversion of natural landscapes into agricultural land release CO_2 stored in trees and soil.
- **Synthetic fertilizers:** The application of synthetic fertilizers leads to nitrous oxide emissions from soil.
- **Rice cultivation**: Flooded rice fields create anaerobic conditions that result in substantial methane emissions.

2.2 Carbon sequestration potential in agricultural land

Despite its role as a contributor to greenhouse gas emissions, agriculture also holds great potential for carbon sequestration. Carbon sequestration is the process by which atmospheric carbon is captured and stored in soil, vegetation, and agricultural practices, mitigating the overall impact of greenhouse gases (Baumber *et al.,* 2020). The main elements of carbon sequestration in agriculture include:

- **Cover crops:** Planting cover crops during fallow periods can enhance soil carbon sequestration.
- **Agroforestry:** Integrating trees into agricultural landscapes can sequester carbon in both biomass and soil.
- **No-till farming:** Reducing or eliminating soil tillage helps maintain soil structure and organic matter, enhancing carbon sequestration.
- **Crop rotation:** Diversifying crop rotations can improve soil health, increase carbon inputs, and reduce the need for synthetic fertilizers.
- **Wetland restoration:** Restoring wetlands on or near agricultural lands can be an effective means of carbon sequestration.

2.3 The need for sustainable farming practices

Recognizing the dual role of agriculture in contributing to emissions and mitigating climate change, there is an urgent need to transition towards sustainable farming practices. These practices are not only environmentally beneficial but also economically viable. Sustainable farming entails:

- **Reducing emissions:** Implementing technologies and practices that minimize emissions from livestock, energy use, and fertilizer application.
- **Soil health management:** Focusing on improving soil health through organic matter enrichment, reduced tillage, and responsible nutrient management.
- **Biodiversity conservation:** Promoting biodiversity through habitat preservation, crop diversity, and integrated pest management.
- **Carbon farming:** Embracing carbon farming techniques that actively sequester carbon, such as afforestation, reforestation, and agroforestry.

- **Policy support:** Governments and institutions should provide incentives and policies that encourage the adoption of sustainable farming practices.

Agriculture's role in climate change is complex, as it is both a source of greenhouse gas emissions and a potential solution through carbon sequestration. By adopting sustainable farming practices, the agricultural sector can contribute significantly to climate change mitigation while ensuring its long-term viability and economic sustainability (Mishra, 2024). The subsequent sections of this study will examine the economic implications and opportunities associated with these sustainable agricultural practices.

3. Carbon Farming Practices

Carbon farming, as a sustainable agricultural approach, encompasses various practices aimed at sequestering carbon dioxide from the atmosphere while promoting agricultural diversification. This section discusses one such practice: Agroforestry.

3.1 Agroforestry

3.1.1 Definition and principles

Agroforestry is a land management system that integrates trees or woody shrubs with agricultural crops or livestock, fostering mutually beneficial interactions between them. It encompasses diverse approaches such as alley cropping, silvopasture, and windbreaks. The fundamental principle is the simultaneous cultivation of trees alongside other agricultural activities, creating a symbiotic ecosystem that enhances sustainability (Therond *et al.*, 2017).

3.1.2 Carbon sequestration potential

Agroforestry stands out as a potent carbon sequestration tool. Trees absorb carbon dioxide during photosynthesis and store it in their biomass and the soil, effectively mitigating climate change. The sequestration potential varies based on factors such as tree species, planting density, and management practices. Over time, a mature agroforestry system can sequester substantial amounts of carbon, contributing to climate change mitigation.

3.1.3 Economic benefits and challenges

Economic benefits:

- **Diversified income streams:** Agroforestry offers farmers multiple revenue streams. In addition to traditional crop or livestock products, they can derive income from timber, fruits, nuts, and other non-timber forest products.
- **Enhanced soil fertility:** Trees in agroforestry systems contribute organic matter to the soil, improving its fertility and reducing the need for chemical fertilizers. This translates into cost savings for farmers.
- **Climate change resilience:** Agroforestry systems are more resilient to extreme weather events, providing a buffer against climate-related risks. This resilience can protect farmers from crop loss and income fluctuations.

- **Carbon credits and payments:** In some regions, carbon markets offer financial incentives for carbon sequestration activities. Farmers participating in agroforestry may be eligible for carbon credits or payments for their carbon sequestration efforts.

Challenges:

- **Long gestation period:** Trees take several years to mature and sequester significant carbon. This long gestation period can pose a challenge for farmers seeking immediate economic returns.
- **Resource intensity:** Establishing and maintaining agroforestry systems may require substantial resources, including land, labour, and capital. Not all farmers may have access to these resources.
- **Market access:** Farmers may face challenges in accessing markets for tree products such as timber and non-timber forest products. Market demand and pricing can be volatile.
- **Knowledge and training:** Successful agroforestry management requires specialized knowledge and skills. Lack of training and education can hinder its adoption.

3.2 Cover crops and reduced tillage

Cover crops and reduced tillage represent fundamental components of carbon farming, offering multifaceted benefits ranging from soil health improvement to enhanced economic viability for farmers.

3.2.1 Soil health improvement and carbon sequestration

Cover crops, often referred to as “green manure”, are non-commercial crops grown primarily to protect and enrich the soil. These crops include legumes like clover, which fix atmospheric nitrogen and improve soil fertility. Additionally, they reduce erosion and promote water infiltration, preventing nutrient runoff and soil degradation (Mishra and Dwivedi, 2025). Reduced tillage practices involve minimizing mechanical soil disruption, such as ploughing, which can release stored carbon and disrupt the soil's natural structure. By reducing or eliminating these practices, farmers can preserve soil organic matter and microbial communities, thereby enhancing overall soil health. These combined efforts result in increased carbon sequestration, as carbon dioxide (CO_2) is drawn from the atmosphere and stored in the soil. As a result, carbon farming practices help mitigate climate change by reducing CO_2 emissions while bolstering the resilience of agricultural ecosystems.

3.2.2 Economic viability for farmers

Transitioning to cover crops and reduced tillage may require initial investments in new equipment and knowledge, but the long-term economic benefits are substantial. Farmers can experience cost savings through reduced fuel consumption and less wear and tear on machinery due to decreased tillage. Moreover, the enhanced soil health resulting from these practices can lead to increased crop yields and reduced dependency on expensive synthetic fertilizers (Nishad *et al.*, 2023). In some cases, farmers can diversify their income streams by selling cover crops as forage or seed crops, further improving economic sustainability. Furthermore, carbon farming practices can open doors to carbon credit markets, where farmers can earn revenue by sequestering carbon and offsetting emissions for other industries (Kremen and Miles, 2012).

3.3 Livestock management

Effective livestock management is integral to carbon farming, as it not only improves grazing practices but also addresses the economic implications of methane reduction.

3.3.1 Improved grazing practices

Traditional, unrestricted grazing can lead to overgrazing, soil compaction, and degraded pastures. Carbon farming emphasizes rotational grazing systems, which allow for better pasture management. Livestock are moved systematically between paddocks, enabling grasslands to recover, promoting biodiversity, and preventing soil erosion (Tiwari *et al.,* 2023). Improved grazing practices not only benefit the environment but also enhance the quality and quantity of forage available to livestock, resulting in healthier and more productive animals.

3.3.2 Methane reduction and economic implications

Livestock, particularly ruminants like cattle, produce methane during digestion, which is a potent greenhouse gas. Implementing dietary changes, such as adding dietary supplements or altering feed composition, can significantly reduce methane emissions (Mishra and Mishra, 2024). For farmers, methane reduction can lead to cost savings, as less energy is lost as methane and more energy is retained for animal growth and productivity. Additionally, participating in carbon credit markets for methane reduction projects can provide an additional revenue stream for livestock operations (Kumar *et al.,* 2023; Mishra, 2024).

3.4 Organic farming

Organic farming is a prominent carbon farming practice that holds significant promise for both enhancing soil carbon enrichment and addressing important economic considerations within the context of sustainable agriculture. In this section, we explain the intricacies of organic farming as a means to sequester carbon and explore the economic implications and opportunities associated with its adoption.

3.4.1 Soil carbon enrichment

Organic farming stands out as a potent tool for increasing soil carbon content. This method prioritizes natural and sustainable techniques, eschewing synthetic chemicals and promoting soil health through various means:

- **Cover crops:** Organic farmers often employ cover crops such as legumes and clover. These cover crops add organic matter to the soil when they decompose, contributing to carbon sequestration. Additionally, their root systems help improve soil structure, further enhancing carbon retention.
- **Compost and manure:** Organic farming places a strong emphasis on composting and the use of animal manure as organic fertilizers. These inputs not only provide essential

nutrients for crops but also introduce organic matter into the soil, facilitating carbon storage.

- **Reduced tillage:** Minimal tillage or no-till practices are common in organic farming. By disturbing the soil less, these techniques minimize carbon loss through oxidation and help maintain a higher carbon content in the soil.
- **Agroforestry:** Integrating trees and perennial plants into organic farming systems enhances carbon sequestration through their long-lasting biomass and deep root systems. Agroforestry practices can also diversify income streams for farmers (Vernooy, 2022).

3.4.2 Economic considerations

While organic farming offers numerous environmental benefits, it also presents a set of economic considerations that farmers must navigate:

- **Transition costs:** Shifting from conventional to organic farming practices can incur initial costs and time investments. Farmers may need to adapt their infrastructure, change their crop rotation systems, and undergo organic certification processes, which can be financially burdensome (Mishra and Mishra, 2023).
- **Premium prices:** Organic produce often commands higher prices in the market due to its perceived environmental and health benefits. This price premium can be a significant economic incentive for farmers to transition to organic practices, potentially offsetting the initial transition costs.
- **Market demand:** Organic farming aligns with the growing consumer demand for sustainably produced food. Capitalizing on this trend can result in increased sales and market opportunities for farmers practicing organic agriculture.
- **Reduced input costs:** Over time, organic farming can lead to reduced input costs as farmers rely less on synthetic pesticides and fertilizers. This can contribute to improved profitability in the long run.
- **Ecosystem services:** Organic farming systems often provide ecosystem services such as enhanced biodiversity, improved water quality, and reduced greenhouse gas emissions. These services can have long-term economic benefits, including potential incentives or payments for environmental stewardship.

Carbon farming practices offer multifaceted benefits, including mitigating climate change, enhancing soil health, and providing economic opportunities for farmers. While challenges exist, the adoption of these practices is essential for building a sustainable and resilient agricultural system.

4. Economic Implications of Carbon Farming

4.1 Cost-benefit analysis of carbon farming practices

Carbon farming, a practice aimed at sequestering carbon dioxide from the atmosphere through various agricultural techniques, has gained substantial attention due to its potential to mitigate climate change while offering economic benefits to farmers. In this section, we examine the economic implications of carbon farming, focusing on a comprehensive cost-benefit analysis of these practices.

4.1.1 Investment costs

- **Initial infrastructure and technology investment:** One of the primary considerations in adopting carbon farming practices is the initial investment required. This encompasses expenses related to infrastructure development, such as the installation of renewable energy systems (solar panels, wind turbines), implementation of conservation tillage, and the incorporation of cover crops. Additionally, farmers may need to invest in specialized equipment and training to effectively manage carbon-sequestering practices.
- **Operational costs:** Alongside infrastructure investments, there are operational expenses to consider. These include ongoing costs associated with maintaining and managing the carbon farming infrastructure, such as routine maintenance for renewable energy systems and cover crop planting. Farmers must also account for labour and management costs required for the proper execution of carbon farming practices (Lin, 2011).
- **Carbon credits certification:** Obtaining certification for carbon credits can be a part of the investment cost. This involves third-party verification and auditing processes to ensure that the carbon sequestration achieved through farming practices meets established standards and can be traded in carbon markets.

4.1.2 Long-term returns

- **Carbon credit revenue:** A significant source of revenue for farmers engaged in carbon farming is the sale of carbon credits. As carbon sequestration is achieved through sustainable practices, farmers can generate carbon credits, which can be sold on carbon markets. The revenue generated from these sales can provide a substantial return on the initial investment.
- **Enhanced soil fertility and crop yields:** Many carbon farming techniques, such as the addition of organic matter through cover cropping and reduced soil disturbance through no-till farming, lead to improved soil health and fertility. This can result in higher crop yields and reduced reliance on expensive synthetic fertilizers and pesticides over the long term, contributing to increased profitability.
- **Diversification and risk mitigation:** Carbon farming often encourages diversification of crops and agricultural activities. This diversification can act as a risk mitigation strategy against climate-related challenges and market fluctuations. For example, rotating crops and incorporating agroforestry can spread risks associated with crop failure or price volatility.
- **Access to grants and incentives:** Governments and environmental organizations may provide grants, subsidies, or incentives to farmers engaged in carbon farming. These

financial incentives can help offset initial investment costs and enhance the overall economic viability of carbon farming practices.

- **Eco-tourism and educational opportunities:** Carbon farming practices that emphasize conservation and sustainability can attract eco-tourism and educational opportunities, providing additional income streams for farmers. These initiatives can include farm tours, workshops, and educational programs, which can generate revenue while fostering public awareness and support for sustainable agriculture.

4.2 Market opportunities for carbon credits

Carbon credits, also known as carbon offsets, represent a tradable commodity that allows organizations and individuals to compensate for their greenhouse gas emissions by investing in carbon sequestration and reduction projects. Carbon farming plays a crucial role in this market, offering a means for agricultural stakeholders to generate revenue while contributing to climate change mitigation.

4.2.1 Carbon offset programs

Carbon offset programs are mechanisms that enable entities to balance their carbon emissions by supporting projects that reduce or remove an equivalent amount of greenhouse gases from the atmosphere. Carbon farming projects, such as reforestation, afforestation, and soil carbon sequestration, qualify as eligible activities for carbon offset programs. Farmers and landowners who implement these practices can generate carbon credits that are tradable on carbon markets (Beillouin *et al.,* 2019). The economic implications of participating in carbon offset programs are significant. Farmers can diversify their income streams by selling carbon credits, which can provide a stable and long-term source of revenue. This additional income can help buffer against fluctuations in traditional agricultural markets, making farming more financially sustainable. Moreover, participation in carbon offset programs can enhance the overall value of agricultural land, as carbon-rich soils and well-maintained forests become more attractive assets.

4.2.2 Carbon trading markets

Carbon trading markets, also known as carbon cap-and-trade systems, represent a more complex but potentially lucrative avenue for carbon farming. In these markets, a government or regulatory body sets a cap on total greenhouse gas emissions and allocates or auctions emission allowances to entities within various sectors of the economy. These entities, including industries and power plants, must hold enough allowances to cover their emissions. If they exceed their allocated allowances, they can purchase additional allowances from entities that have surplus credits. Agricultural operations that sequester carbon can participate in carbon trading markets by registering as carbon market participants. They can generate carbon credits through sustainable land management practices and subsequently sell these credits to entities seeking to offset their emissions. The economic benefit of carbon trading for farmers lies in the potential for significant profits, especially as the demand for carbon credits increases with growing climate change concerns (Barghouti *et al.,* 2004). However, participating in carbon trading markets requires understanding complex regulations and compliance requirements. Farmers must accurately measure and verify their carbon sequestration efforts, which can entail initial costs for monitoring and reporting. Additionally, the profitability of carbon trading depends on market dynamics, including the price of carbon allowances, which can fluctuate over time.

4.3 Government incentives and policies

India, as an agrarian economy, has recognized the importance of carbon farming in mitigating climate change and promoting sustainable agriculture. To this end, the government has implemented a range of incentives and policies to support carbon farming initiatives across the country.

4.3.1 Subsidies and grants

One of the primary ways in which the Indian government encourages carbon farming is through financial support in the form of subsidies and grants. These incentives aim to reduce the financial burden on farmers who wish to adopt carbon sequestration practices in their agricultural operations. The following are some major elements of this support system:

- **Carbon farming subsidies:** The government offers subsidies to farmers who implement carbon farming techniques, such as agroforestry, cover cropping, and reduced tillage. These subsidies cover a portion of the expenses related to adopting and maintaining these practices.
- **Research and development grants:** In order to advance carbon farming methods and technologies, the government provides grants to research institutions and organizations working on innovative approaches to sequestering carbon in agricultural soils. These grants facilitate the development of cost-effective and efficient carbon farming solutions.
- **Training and education grants:** To ensure that farmers have access to the knowledge and skills required for successful carbon farming, the government offers grants to support training programs and workshops. These initiatives empower farmers with the necessary expertise to implement carbon sequestration practices effectively.

4.3.2 Regulatory support

In addition to financial incentives, the Indian government has implemented various regulatory measures to create a conducive environment for carbon farming and sustainable agricultural diversification:

- **Emissions trading framework:** India has been exploring the possibility of establishing emissions trading schemes (ETS) at the regional and national levels. These ETS can create a market for carbon credits generated by carbon farming activities. Farmers can sell their carbon credits to industries seeking to offset their emissions, providing an additional revenue stream.

- **Carbon offsetting standards:** The government has developed standards and guidelines for carbon offset projects, including those related to agriculture. These standards ensure transparency, credibility, and the accurate measurement of carbon sequestration, making it easier for farmers to participate in carbon offset markets.
- **Land use planning:** Land use planning policies promote the incorporation of carbon farming practices into regional and local land management strategies. This includes zoning regulations that encourage afforestation, reforestation, and sustainable land use practices that sequester carbon.

India's approach to carbon farming reflects its commitment to sustainable agriculture and climate change mitigation. By offering subsidies, grants, and regulatory support, the government encourages farmers to embrace carbon-sequestering practices while fostering economic growth and diversification in the agricultural sector. These policies not only contribute to a more sustainable future but also create opportunities for rural communities and businesses to thrive in a carbon-conscious world (Wanger *et al.*, 2022). Carbon farming presents a multifaceted economic landscape, encompassing initial investment costs, long-term returns, market opportunities through carbon credits, and government incentives and policies. To fully harness the economic benefits of carbon farming and drive sustainable agricultural diversification, stakeholders must carefully assess and navigate these economic implications. This comprehensive analysis is essential for informed decision-making and the successful integration of carbon farming into modern agriculture (Mishra and Mishra, 2024).

5. Challenges and Barriers

In the pursuit of carbon farming as a sustainable agricultural diversification strategy, several challenges and barriers must be addressed to ensure its successful implementation. These challenges encompass technical issues, economic and financial barriers, as well as policy and regulatory obstacles.

5.1 Technical challenges

5.1.1 Knowledge and training

- Carbon farming involves implementing specific agricultural practices aimed at sequestering carbon in soil and vegetation. Farmers may lack the necessary knowledge and training to effectively adopt these practices.
- Training programs and educational initiatives are needed to disseminate information about carbon farming techniques, their benefits, and how to implement them. This might include workshops, online resources, and partnerships with agricultural extension services.

5.1.2 Infrastructure and equipment

- Some carbon farming practices require specialized infrastructure and equipment, such as precision agriculture tools for no-till farming or the installation of agroforestry systems.

- The cost of acquiring and maintaining such equipment can be a significant barrier for many farmers, particularly those in resource-constrained environments.
- Governments and organizations can provide financial incentives or subsidies to help farmers access the necessary infrastructure and equipment, making carbon farming more feasible.

5.2 Economic and financial barriers

5.2.1 Initial investment

- Implementing carbon farming practices often requires an initial investment in new infrastructure, equipment, and technology. These upfront costs can deter farmers from adopting sustainable practices.
- Financial mechanisms like grants, low-interest loans, or tax incentives can help offset the initial investment and encourage more widespread adoption of carbon farming.

5.2.2 Market uncertainties

- The economic viability of carbon farming is closely tied to the carbon market, which can be volatile and uncertain.
- Farmers may hesitate to invest in carbon farming if they are unsure about the long-term profitability or the stability of carbon credit prices.
- Policymakers can provide stability to the carbon market through regulatory mechanisms and by setting a consistent price floor for carbon credits, thereby reducing market uncertainties.

5.3 Policy and regulatory obstacles

5.3.1 Lack of supportive policies

- Carbon farming may not have adequate policy support in some regions, making it difficult for farmers to transition to these practices.
- Governments can play a crucial role by implementing policies that promote and incentivize carbon farming. This could include subsidies, tax credits, or payments for ecosystem services to reward farmers for sequestering carbon.

5.3.2 Land use regulations

- Existing land use regulations may hinder the adoption of carbon farming practices. Zoning laws and restrictions on land use can limit the ability of farmers to implement agroforestry or reforestation efforts.
- Policymakers should review and adjust land use regulations to accommodate carbon farming practices while still considering the broader environmental and social impacts.

Addressing these challenges and barriers is essential for the successful integration of carbon farming into sustainable agricultural diversification strategies. Collaboration among farmers, governments, research institutions, and environmental organizations is crucial to overcome these obstacles and realize the potential economic and environmental benefits of carbon farming.

6. Strategies for Promoting Carbon Farming Adoption

Carbon farming is a promising approach to not only reduce greenhouse gas emissions but also enhance the sustainability and economic viability of agriculture. To encourage its adoption, various strategies need to be implemented. Three major strategies for promoting carbon farming adoption as following:

6.1 Education and outreach

6.1.1 Farmer training programs

Implementing farmer training programs is a fundamental step in promoting carbon farming adoption. These programs are designed to educate farmers about the principles and practices of carbon farming. They typically include:

- **Workshops and seminars:** Organizing workshops and seminars led by experts in carbon farming can provide farmers with valuable insights into carbon sequestration techniques, soil health improvement, and sustainable land management practices.
- **On-farm demonstrations:** Practical, on-farm demonstrations allow farmers to see carbon farming techniques in action. They can learn how to implement these practices effectively on their own land.
- **Technical assistance:** Providing farmers with access to technical experts who can offer guidance on soil testing, crop rotation, and other carbon farming strategies can be invaluable.

6.1.2 Public awareness campaigns

Public awareness campaigns play a crucial role in garnering support for carbon farming. These campaigns aim to inform the general public about the benefits of carbon farming and how it contributes to environmental sustainability. Major components of such campaigns include:

- **Informational materials:** Creating brochures, pamphlets, and websites that explain carbon farming concepts, benefits, and its role in mitigating climate change.
- **Media outreach:** Engaging with local media outlets to raise awareness through news articles, interviews, and feature stories on successful carbon farming projects.
- **Community engagement:** Organizing community events, such as field trips to carbon farming sites or informational workshops, to involve the local community and build support.

6.2 Financial support mechanisms

6.2.1 Low-interest loans

Access to affordable financing is critical for farmers looking to transition to carbon farming practices. Low-interest loans can help cover the initial costs associated with implementing carbon-friendly techniques. These loans may be offered by government agencies or financial institutions (Sarial, 2019). Major considerations include:

- **Loan eligibility criteria:** Defining eligibility criteria that prioritize farmers interested in adopting carbon farming practices and providing favourable interest rates to incentivize participation.
- **Loan repayment terms:** Offering flexible repayment terms that align with the seasonal nature of farming and the expected economic benefits of carbon farming.

6.2.2 Incentive programs

Incentive programs are financial rewards or subsidies designed to motivate farmers to engage in carbon farming. These programs can take various forms, such as:

- **Carbon credit payments:** Providing farmers with payments based on the amount of carbon they sequester through their farming practices.
- **Tax incentives:** Offering tax breaks or deductions to farmers who adopt carbon farming practices, thereby reducing their financial burden.
- **Equipment grants:** Offering grants to cover the cost of purchasing equipment and technologies that enhance carbon sequestration.

6.3 Policy advocacy

6.3.1 Lobbying for supportive legislation

Advocacy efforts are essential for creating an enabling policy environment for carbon farming. Farmers and environmental organizations can lobby for legislative changes that promote and incentivize carbon farming. Main actions may include:

- **Proposing legislation:** Drafting and presenting bills or policy proposals that recognize the value of carbon farming and offer incentives or subsidies.
- **Coalition building:** Forming alliances with other stakeholders, including environmental groups, to strengthen advocacy efforts and demonstrate broad support.

6.3.2 Government-industry collaboration

Government-industry collaboration is crucial to bridge the gap between policy development and on-the-ground implementation. This collaborative approach involves:

- **Task forces and advisory panels:** Establishing committees or advisory panels that bring together government officials, farmers, scientists, and industry representatives to develop and refine carbon farming policies.
- **Funding allocation:** Allocating government funds to support research, demonstration projects, and infrastructure development related to carbon farming.
- **Monitoring and reporting:** Implementing systems for monitoring and reporting on carbon farming outcomes to ensure that policies remain effective and adaptable.

Promoting the adoption of carbon farming practices requires a multifaceted approach, encompassing education and outreach, financial support mechanisms, and policy advocacy. These strategies, when implemented effectively, can help farmers transition to more sustainable agricultural practices while mitigating climate change.

7. Future Prospects and Opportunities

In this section, we will discuss the potential future prospects and opportunities for carbon farming, focusing on technological advancements, global market trends, and climate resilience and adaptation strategies.

7.1 Technological advancements

7.1.1 Precision agriculture and carbon monitoring

Precision agriculture involves the use of advanced technologies such as GPS, remote sensing, and data analytics to optimize farming operations. In the context of carbon farming, precision agriculture plays a crucial role in enhancing the efficiency of carbon sequestration and reducing emissions. Farmers can employ precision agriculture to:

- **Monitor soil health and carbon content:** High-tech sensors and satellite imagery can help farmers assess the carbon content in their soils accurately. This data can inform carbon sequestration strategies and enable farmers to make informed decisions about crop selection and land management practices.
- **Reduce emissions:** Precision agriculture allows for precise application of fertilizers and pesticides, minimizing overuse and reducing greenhouse gas emissions associated with their production and application.
- **Implement carbon-friendly crop rotation:** Advanced analytics can help farmers identify optimal crop rotation patterns that enhance soil health and carbon sequestration.

7.1.2 Innovative farming practices

Innovative farming practices go beyond traditional approaches and incorporate sustainable and carbon-conscious methods. These practices can include:

- **No-till farming:** By avoiding ploughing and reducing soil disturbance, no-till farming can help sequester carbon in the soil and reduce carbon emissions from fossil fuel-powered machinery.
- **Cover cropping:** Planting cover crops during fallow periods can protect the soil, enhance carbon sequestration, and improve overall soil health.
- **Agroforestry:** Integrating trees and shrubs into farming landscapes not only sequesters carbon in biomass but also provides additional income streams through timber and non-timber forest products.

7.2 Global market trends

7.2.1 Growing demand for sustainable agriculture

Consumers and food companies are increasingly prioritizing sustainable and environmentally friendly agricultural practices. Carbon farming aligns with this trend by offering a way to produce food while mitigating climate change. Future opportunities in this regard may include:

- **Premium pricing:** Carbon-neutral or carbon-negative products may command premium prices in the market, providing a financial incentive for farmers to adopt carbon farming practices.
- **Certification and labelling:** Certification programs and labels for carbon-friendly agricultural products can help consumers make informed choices and drive demand for such products (Nishad *et al.,* 2011).

7.2.2 International climate agreements

International climate agreements, such as the Paris Agreement, create a global framework for addressing climate change. These agreements can influence agricultural policies and trade dynamics, potentially opening up new opportunities for carbon farming:

- **Carbon trading markets:** The establishment of international carbon markets may allow farmers to earn carbon credits by sequestering carbon in their fields, providing an additional revenue stream.
- **Climate finance:** International funding mechanisms may support agricultural projects that prioritize carbon sequestration, enabling farmers to access financial resources for adopting sustainable practices.

7.3 Climate resilience and adaptation

7.3.1 Carbon farming as a climate-resilient strategy

Carbon farming can enhance climate resilience by improving soil health, water retention, and overall ecosystem stability. This resilience can help farmers adapt to the changing climate, including more frequent extreme weather events.

- **Drought resilience:** Healthy soils with increased organic matter can better retain moisture, making crops more resilient to drought conditions.
- **Flood mitigation:** Improved soil structure can reduce the risk of erosion and flooding during heavy rainfall events.

7.3.2 Economic resilience for farmers

Carbon farming can also enhance economic resilience for farmers by diversifying their income sources and reducing dependency on volatile commodity markets:

- **Carbon credit revenue:** Selling carbon credits can provide farmers with a stable income source that is less susceptible to price fluctuations compared to traditional agricultural commodities.
- **Multiple income streams:** Integrating carbon farming with other sustainable practices, such as agroforestry or eco-tourism, can create multiple revenue streams and reduce financial risk.

The future prospects and opportunities for carbon farming are promising, driven by technological advancements, evolving market trends, and the need for climate resilience. Farmers who embrace carbon farming practices stand to benefit both economically and environmentally, contributing to a more sustainable and resilient agricultural sector (Wang *et al.*, 2022).

Conclusion:

Agriculture is a significant contributor to greenhouse gas emissions, but it also holds the key to sequestering carbon and promoting sustainable farming practices. Carbon farming practices, including agroforestry, cover crops, livestock management, and organic farming, offer multifaceted benefits in terms of carbon sequestration and economic viability for farmers. Economic implications of carbon farming are multifaceted, with costs and benefits to consider. Cost-benefit analyses reveal potential long-term returns, while emerging market opportunities for carbon credits provide financial incentives. Government support in the form of subsidies, grants, and regulatory backing further enhances the economic feasibility of carbon farming. Nevertheless, challenges and barriers persist, ranging from technical limitations to initial investment hurdles and policy obstacles. To promote widespread adoption, strategies such as education, financial support, and policy advocacy must be employed to create an enabling environment for carbon farming. The future prospects and opportunities in carbon farming are promising. Technological advancements in precision agriculture and carbon monitoring, coupled with evolving global market trends and climate resilience considerations, make carbon farming an attractive and sustainable strategy for farmers. As the world confronts the urgent need for climate action, carbon farming stands as a beacon of hope, offering not only ecological benefits but also economic resilience for the agricultural sector. Embracing carbon farming represents a pivotal step towards a more sustainable and climate-resilient future.

References:

1. Adhikari, L., Komarek, A. M., de Voil, P., & Rodriguez, D. (2023). A framework for the assessment of farm diversification options in broadacre agriculture. *Agricultural Systems*, *210*, 103724, DOI: 10.1016/j.agsy.2023.103724.
2. Barghouti, S., Kane, S., Sorby, K., & Ali, M. (2004). Agricultural diversification for the poor guidelines for practitioners.
3. Barnes, A. P., McMillan, J., Sutherland, L. A., Hopkins, J., & Thomson, S. G. (2022). Farmer intentional pathways for net zero carbon: Exploring the lock-in effects of forestry and renewables. *Land Use Policy*, *112*, 105861, DOI: 10.1016/j.landusepol.2021.105861.
4. Baumber, A., Waters, C., Cross, R., Metternicht, G., & Simpson, M. (2020). Carbon farming for resilient rangelands: people, paddocks and policy. *The Rangeland Journal*, *42*(5), 293-307, DOI: 10.1071/RJ20034.
5. Beillouin, D., Ben-Ari, T., & Makowski, D. (2019). Evidence map of crop diversification strategies at the global scale. *Environmental Research Letters*, *14*(12), 123001, DOI: 10.1088/1748-9326/ab4449.

6. Bowman, M. S., & Zilberman, D. (2013). Economic factors affecting diversified farming systems. *Ecology and society*, *18*(1), DOI: 10.5751/ES-05574-180133.
7. Cusworth, G., Garnett, T., & Lorimer, J. (2021). Agroecological break out: Legumes, crop diversification and the regenerative futures of UK agriculture. *Journal of Rural Studies*, *88*, 126-137, DOI: 10.1016/j.jrurstud.2021.10.005.
8. Hufnagel, J., Reckling, M., & Ewert, F. (2020). Diverse approaches to crop diversification in agricultural research. A review. *Agronomy for Sustainable Development*, *40*, 1-17.
9. Ian Tiseo and 26, J. (2023) *India: GHG Emission shares by Sector*, *Statista*. Available at: https://www.statista.com/statistics/955980/india-distribution-of-ghg-emissions-by-sector/ (Accessed: 28 September 2023).
10. IPCC. (2023). Synthesis Report of the IPCC 6th Assessment Report (AR6) Summary for Policymakers. In *IPCC*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf
11. Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecology and society*, *17*(4), DOI: 10.5751/ES-05035-170440.
12. Kremen, C., Iles, A., & Bacon, C. (2012). Diversified farming systems: an agroecological, systems-based alternative to modern industrial agriculture. *Ecology and society*, *17*(4), DOI: 10.5751/ES-05103-170444.
13. Kumar, N., Kushwaha, R. R., Meena, N. R., Mishra, H., & Yadav, A. P. S. (2023). A study on costs and returns of paddy cultivation in Ambedkar Nagar district of Uttar Pradesh. *International Journal of Statistics and Applied Mathematics*, *SP*, *8*(3), 107-111.
14. Lin, B. B. (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. *BioScience*, *61*(3), 183-193, DOI: 10.1525/bio.2011.61.3.4.
15. Liu, C., Cutforth, H., Chai, Q., & Gan, Y. (2016). Farming tactics to reduce the carbon footprint of crop cultivation in semiarid areas. A review. *Agronomy for Sustainable Development*, *36*, 1-16.
16. Mishra, H. (2024). Nanobiostimulants and Precision Agriculture: A Data-Driven Approach to Farming and Market Dynamics. In *Nanobiostimulants: Emerging Strategies for Agricultural Sustainability* (pp. 365-398). Cham: Springer Nature Switzerland, DOI: 10.1007/978-3-031-68138-7_16.
17. Mishra, H. (2024). The Role of Ethnoeconomics in Promoting Sustainable Consumption and Production Patterns: A Pathway to Environmental Protection and Economic Prosperity. *Sustainable Development*. In *Seen Through the Lenses of Ethnoeconomics and the Circular Economy* (pp. 91-123). Cham: Springer Nature Switzerland, DOI: 10.1007/978-3-031-72676-7_6.

18. Mishra, H., & Dwivedi, S. (2025). Economic Analysis of AI Integration in Internet of Drones (IoD). In *Machine Learning for Drone-Enabled IoT Networks* (pp. 169-190). Springer, Cham, DOI: 10.1007/978-3-031-80961-3_9.
19. Mishra, H., & Mishra, D. (2023). Artificial intelligence and machine learning in agriculture: Transforming farming systems. *Res. Trends Agric. Sci*, *1*, 1-16.
20. Mishra, H., & Mishra, D. (2024). AI for Data-Driven Decision-Making in Smart Agriculture: From Field to Farm Management. In *Artificial Intelligence Techniques in Smart Agriculture* (pp. 173-193). Singapore: Springer Nature Singapore, DOI: 10.1007/978-981-97-5878-4_11.
21. Mishra, H., & Mishra, D. (2024). Sustainable Smart Agriculture to Ensure Zero Hunger. In *Sustainable Development Goals* (pp. 16-37). CRC Press, DOI: 10.1201/9781003468257-2.
22. Mishra, H., & Mishra, D. (2025). Robotics, Drones, Remote Sensing, GIS, and IoT Tools for Agricultural Operations and Water Management. In *Integrated Land and Water Resource Management for Sustainable Agriculture Volume 2* (pp. 21-49). Singapore: Springer Nature Singapore, DOI: 10.1007/978-981-97-9800-1_2.
23. Mishra, H., Mishra, D., Tiwari, A. K., & Nishad, D. C. (2025). Cost–Benefit Analysis of Sensing and Data Collection with Drones for IoT Applications. In *Machine Learning for Drone-Enabled IoT Networks* (pp. 141-168). Springer, Cham, DOI: 10.1007/978-3-031-80961-3_8.
24. Nishad, D. C., Mishra, H., Tiwari, A. K., & Mishra, D. (2011). Post-harvest Management: Enhancing food security and sustainability. *Advances in Agriculture Sciences Volume II*, *24*(4), 136.
25. Nishad, D. C., Mishra, H., Tiwari, A. K., & Pandey, A. (2023). Towards sustainable agriculture: Mitigating the adverse effects of stubble burning in India. *Research trends in environmental science*, *1*, 42-48.
26. Rosa-Schleich, J., Loos, J., Mußhoff, O., & Tscharntke, T. (2019). Ecological-economic trade-offs of diversified farming systems–a review. *Ecological Economics*, *160*, 251-263, DOI: 10.1016/j.ecolecon.2019.03.002.
27. Sarial, A. K. (2019). Challenges and opportunities in crop diversification. *Himachal Journal of Agricultural Research*, *45*(1&2), 1-14.
28. Tacconi, F., Waha, K., Ojeda, J. J., & Leith, P. (2022). Drivers and constraints of on-farm diversity. A review. *Agronomy for Sustainable Development*, *42*(1), 2, DOI: 10.1007/s13593-021-00736-6.
29. Therond, O., Duru, M., Roger-Estrade, J., & Richard, G. (2017). A new analytical framework of farming system and agriculture model diversities. A review. *Agronomy for sustainable development*, *37*, 1-24.

30. Tiwari, A. K., Mishra, H., & Nishad, D. C. (2011). Market dynamics and consumer perceptions of organic produce in contemporary agriculture. *Advances in Agriculture Sciences Volume II*, *24*(4), 120.
31. Tiwari, A. K., Mishra, H., Nishad, D. C., & Pandey, A. (2023). Sustainable water management in agriculture: irrigation techniques and water conservation. *Dr. Ajay B. Jadhao*, *53*.
32. Vernooy, R. (2022). Does crop diversification lead to climate-related resilience? Improving the theory through insights on practice. *Agroecology and Sustainable Food Systems*, *46*(6), 877-901, DOI: 10.1080/21683565.2022.2076184.
33. Wang, R., Zhang, Y., & Zou, C. (2022). How does agricultural specialization affect carbon emissions in China? *Journal of Cleaner Production*, *370*, 133463, DOI: 10.1016/j.jclepro.2022.133463.
34. Wanger, T., He, X., Weisser, W., Zou, Y., Fan, S., & Crowther, T. (2022). Integrating Agricultural Diversification in China's Major Policies for Sustainable and Resilient Crop Production.
35. Yang, X., Gao, W., Zhang, M., Chen, Y., & Sui, P. (2014). Reducing agricultural carbon footprint through diversified crop rotation systems in the North China Plain. *Journal of Cleaner Production*, *76*, 131-139, DOI: 10.1016/j.jclepro.2014.03.063.

(ISBN: 978-93-48620-17-0)

ECONOMIC BENEFITS OF DUAL PRODUCTION AND LIVESTOCK GRAZING FOR SUSTAINABLE NATURAL RESOURCE MANAGEMENT

Deep Chand Nishad[1], Harshit Mishra*[2],
Sandeep Kumar[3], Shivam Srivastav[4] and Kartikay Srivastava[5]

[1]Department of Agronomy, Shri Durga Ji Post Graduate College, Chandeshwar, Azamgarh (U.P.) -276 128, Affiliated to Veer Bahadur Singh Purvanchal University, Jaunpur, U.P.

[2]Department of Agricultural Economics, College of Agriculture, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, U.P. 224 229

[3]Department of Agronomy, Shri Durga Ji Post Graduate College, Chandeshwar, Azamgarh, 276 128, Affiliated to Maharaja Suhel Dev University, Azamgarh, U.P.

[4]Department of Genetics and Plant Breeding, Bihari Lal Smarak Kisan P. G. College, Amadarveshpur, Ambedkar Nagar (U.P.) – 224 139, Affiliated to Dr. Rammanohar Lohia Avadh University Ayodhya, U.P.

[5]Department of Genetics and Plant Breeding, Shri Durga Ji Post Graduate College, Chandeshwar, Azamgarh (U.P.) – 276 128, Affiliated to Veer Bahadur Singh Purvanchal University, Jaunpur, U.P.

*Corresponding author E-mail: wehars@gmail.com

Abstract:

Natural Resource Management (NRM) is a vital and growing field, with global spending projected to reach $1.2 trillion by 2030. In India, a resource-rich country, the integration of dual production and livestock grazing offers a promising strategy for sustainable development. Dual production—combining crop cultivation and livestock rearing within the same system—enhances productivity, optimizes resources, and diversifies income. Historical practices such as crop-livestock integration, silvopastoral systems, and agroforestry demonstrate this approach's evolution. Livestock grazing systems, including rotational and adaptive grazing, significantly influence ecological balance and productivity. However, environmental impacts necessitate careful economic and ecological assessment. The economic benefits include improved efficiency, reduced costs, and increased resilience. Methods like cost-benefit analysis and return on investment help evaluate sustainability. Effective policy frameworks, government incentives, and land use planning are crucial for successful implementation. Despite the advantages, challenges such as resource competition, biodiversity conservation, climate resilience, and market dynamics must be addressed. Future prospects lie in technological innovation, precision agriculture, and meeting the global demand for sustainable food systems. Continued research and development are essential to refine these integrated approaches and ensure long-term sustainability in NRM.

Keywords: Dual Production, Economic Benefits, Livestock Grazing, NRM, Sustainable Agriculture

1. Introduction:

Dual production and livestock grazing represent a sustainable approach to natural resource management (NRM) by integrating livestock production with ecosystem services. This practice is gaining global recognition due to its economic and environmental benefits. A major advantage is the potential to enhance productivity. By linking livestock grazing with services such as carbon sequestration, water filtration, and biodiversity conservation, these systems improve soil health, forage yield, and animal performance, leading to higher productivity than traditional systems (Mishra *et al.,* 2011). Another significant benefit is income diversification. Farmers can earn from livestock sales, ecosystem services, and ecotourism (Kellert *et al.,* 2000), creating resilience to market fluctuations. Additionally, these systems reduce costs by minimizing the need for external inputs like fertilizers and feed, thus enhancing economic sustainability. Dual production systems also exhibit greater resilience to climate change and environmental stressors than conventional grazing systems. By enhancing ecosystem health, they improve adaptability (Devendra and Chantalakhana, 2002). According to a 2021 FAO report, the global market for dual production and livestock grazing products and services is valued at over US$10 billion, with substantial growth expected.

Various models of these systems are practiced globally, tailored to specific ecological and economic contexts. Silvopastoral systems, combining livestock grazing with tree and shrub production, are common in Latin America and Africa (Franzluebbers, 2007). Trees provide shade, and shrubs offer additional forage, improving both ecological and economic outcomes. Agroforestry systems, which integrate livestock with crops, are widespread in Asia and Latin America. Livestock contribute to fertilization and weeding, while crops offer forage (Burark *et al.,* 2023). In North America, Europe, and Australia, managed grazing systems control grazing intensity and timing to optimize both productivity and ecological health (Mishra and Mishra, 2024). These systems are economically beneficial worldwide. In the U.S., silvopastoral systems generate carbon credits; farmers earn income by selling credits for sequestered carbon. In Kenya, agroforestry integrated into coffee plantations improves soil fertility and pest resistance, increasing yield and quality. In Australia, managed grazing enhances rangeland conditions, boosting livestock productivity and income (Kumar *et al.,* 2023; Turner, 2004). The economic outlook is promising. Rising demand for sustainably produced food creates more opportunities for adopting these systems (Bellamy *et al.,* 2001). As awareness grows, so do prospects for sustainable and profitable agriculture (Farina, 2000; Li *et al.,* 2008).

India, with its agrarian economy and vast livestock population, is well-positioned to benefit from these systems. Integrated farming involving dual production and livestock grazing can transform rural livelihoods and address socio-economic and environmental issues. A study by the International Center for Tropical Agriculture highlights that these systems can generate net incomes up to 50% higher than traditional cropping systems (Devendra, 2011). They also promote food security and poverty reduction (Mishra and Mishra, 2023). Despite these benefits, adoption in India is limited due to challenges such as lack of credit, inadequate technical skills, poor market access, and policy constraints. Overcoming these barriers is crucial to unlocking their full potential (Dumont *et al.,* 2013). Recognizing this, the Indian government has launched initiatives to promote these systems (Dixon and Wood, 2003). These include financial support, training programs, research funding, and market development for livestock products (Reddy and Reddy, 2016). These efforts reflect a strong commitment to sustainable agriculture. Widespread adoption could greatly enhance economic, social, and environmental sustainability in rural India (Nishad *et al.,* 2011). Government support is critical to realizing this potential, paving the way for a resilient and sustainable agricultural sector (Topp-Jorgensen *et al.,* 2005).

Dual production and livestock grazing are multifaceted approaches to sustainable NRM. As environmental challenges grow alongside global food demand, these systems offer economically viable solutions (Chapin III *et al.,* 2009). This text explores their evolution, practices, and challenges, offering insights into their sustainability benefits (Jose and Dollinger, 2019; Mishra and Mishra, 2024). Dual production involves crop-livestock integration within a shared agro-ecosystem, rooted in historical agricultural practices (Kangalawe and Liwenga, 2005). The various forms, including silvopastoral and agroforestry systems, provide mutual benefits. We also analyze their challenges, highlighting their role in sustainability. Livestock grazing, a cornerstone of sustainable farming, is examined through systems like rotational, continuous, and adaptive grazing, each with distinct ecological and economic outcomes (Stone and Stone, 2011). Assessing environmental impacts and economic outcomes of grazing practices is key. We explore their role in boosting productivity, diversifying income, optimizing resource use, and creating value-added opportunities. The discussion also includes economic analysis tools, policy implications, and future trends. Technology, data, and innovation will be essential in advancing sustainable practices and meeting global food demands (Mishra and Mishra, 2024). Continued research and development are crucial for building a resilient agricultural future.

2. Dual Production: Concepts and Practices

2.1 Definition and overview

Dual production, in the context of sustainable NRM, refers to a multifaceted approach that combines two major activities: agricultural or livestock production and the sustainable management of natural resources. This approach acknowledges the interconnectedness of agriculture and natural ecosystems and seeks to optimize both for the benefit of the environment and the economy (Tiwari *et al.,* 2011). The main idea is to strike a balance between agricultural production and the preservation of natural resources, ensuring long-term sustainability.

Overview of dual production:

1. **Integration of agriculture and NRM:** Dual production focuses on integrating agricultural activities, such as crop cultivation and livestock farming, with the conservation and sustainable management of natural resources like soil, water, and biodiversity. The goal is to create a mutually beneficial relationship where agricultural practices support and enhance the health and functioning of the ecosystem.
2. **Sustainable agriculture:** Sustainable farming practices are at the core of dual production. These practices include crop rotation, organic farming, reduced chemical inputs, and the use of cover crops to improve soil health and reduce environmental degradation. By adopting these methods, dual production aims to maintain agricultural productivity while minimizing negative environmental impacts.
3. **Holistic approach:** Dual production takes a holistic approach to land management. It recognizes the interplay between agricultural activities and the environment, emphasizing the importance of ecosystem services like pollination, water purification, and carbon sequestration in supporting agricultural productivity.
4. **Economic and environmental benefits:** The concept of dual production aims to achieve a win-win situation where both economic and environmental benefits are realized. It promotes the use of sustainable practices that can enhance crop yields and livestock productivity while simultaneously conserving natural resources and reducing greenhouse gas emissions.

2.2 Historical perspective

The idea of dual production, blending agriculture and NRM, has deep historical roots and has evolved over time. It draws inspiration from traditional and indigenous agricultural practices, as well as modern sustainability movements (Herrero *et al.*,2013). Table 1 represents a brief historical perspective on dual production practices.

Table 1: Historical perspective of dual production practices

Time period	Region	Dual production practices
10,000 BC	Fertile Crescent	Domestication of sheep and goats, combined with crop production
3000 BC	Indus Valley Civilization	Integrated crop-livestock systems, with cattle used for ploughing and manure production
1000 BC	China	Development of the rice-azolla-fish system, which combines rice production with aquaculture and livestock grazing
500 BC	Greece and Rome	Use of sheep and goats to graze fallows and provide manure for crops

1000 AD	Islamic world	Development of complex agroforestry systems that combine crops, trees, and livestock
1500 AD	Europe	Enclosure movement leads to separation of crop and livestock production, with negative consequences for soil fertility and biodiversity
1800 AD	North America	Settlers adopt Native American dual production practices, such as intercropping corn and beans and using bison to fertilize crops
1900 AD	Global	Green Revolution leads to widespread adoption of monocultures and synthetic fertilizers, which reduces soil fertility and biodiversity
2000 AD	Global	Growing interest in sustainable agriculture practices, including dual production

1. **Traditional farming systems:** Many traditional farming systems across the world have long incorporated dual production principles. For example, Indigenous agricultural practices often involved rotational farming, agroforestry, and mixed-crop farming, which inherently balanced agriculture with NRM.
2. **Green revolution and intensive agriculture:** In the mid-20th century, the Green Revolution brought significant advances in agricultural productivity but often at the expense of the environment. This era led to increased chemical use, monoculture cropping, and resource degradation, highlighting the need for more sustainable practices.
3. **Rise of sustainable agriculture:** The late 20th century saw the emergence of the sustainable agriculture movement, which emphasized the importance of balancing agricultural production with environmental stewardship. Concepts like organic farming, integrated pest management, and conservation tillage gained prominence during this time.
4. **Modern dual production practices:** Today, dual production is a response to the shortcomings of intensive agriculture. Farmers and land managers are increasingly adopting practices that emphasize the symbiotic relationship between agriculture and the environment. This includes initiatives like precision agriculture, agroecology, and the use of cover crops to enhance soil health.
5. **Policy and research support:** Governments, environmental organizations, and research institutions have recognized the significance of dual production. They have been supporting initiatives that promote sustainable agriculture, agroecological practices, and integrated NRM.

2.3 Dual production strategies

Dual production strategies involve the concurrent management of multiple agricultural activities, typically crop production and livestock grazing. These strategies are designed to optimize resource utilization and enhance sustainability (Thornton, 2010; Mishra, 2025). The following sub-sections explore three major dual production strategies:

2.3.1 Crop-livestock integration

Definition and overview: Crop-livestock integration is a sustainable agricultural practice where crops and livestock are managed on the same piece of land. This practice promotes synergy between crop production and livestock rearing. For example, crop residues such as maize stalks can be used as fodder for cattle, and cattle manure can be used to fertilize the fields. This approach helps to create a closed nutrient cycle.

Historical perspective: The integration of crops and livestock dates back to ancient agricultural systems. Traditional farms often combined crop cultivation with animal husbandry. It was only with the advent of industrial agriculture in the 20th century that these two practices became increasingly separated. Today, there is a resurgence of interest in crop-livestock integration due to its environmental and economic benefits.

Economic benefits: Crop-livestock integration can have many economic advantages. First, it increases resource use efficiency. For example, crop residues not suitable for human consumption can be used to feed livestock, reducing waste and enhancing productivity (Fig. 1). Second, it diversifies income sources for farmers. They can earn money from both crop sales and livestock products, such as milk and meat. Third, it enhances risk management as farmers are less vulnerable to market fluctuations affecting a single commodity.

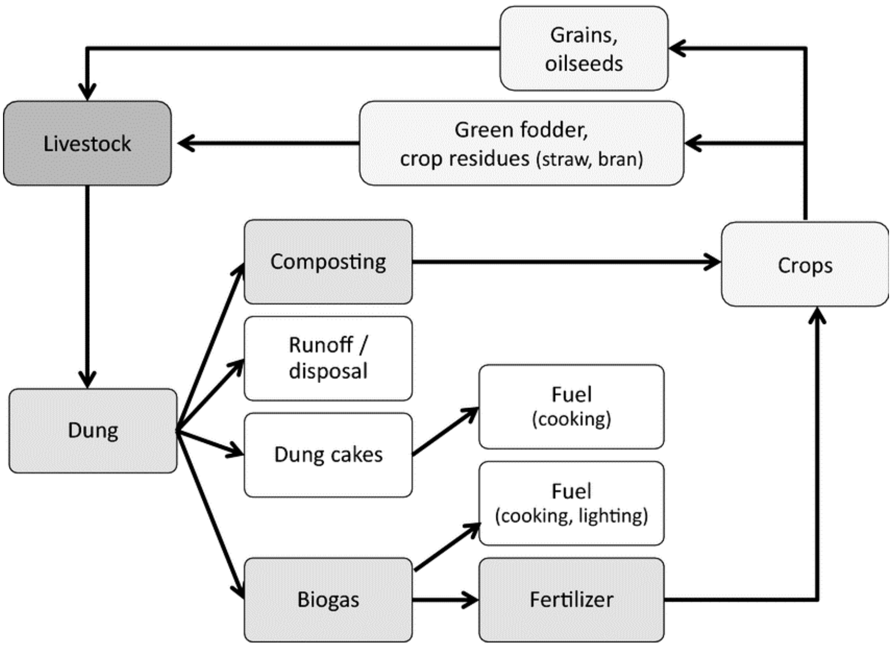

Fig.1: Crop-livestock integration in India (Source: Prasad *et al.*, 2019)

2.3.2 Silvopastoral systems

Definition and overview: Silvopastoral systems combine trees or forests with livestock grazing. In these systems, trees are strategically planted in pastures, providing shade and additional forage resources for livestock (Fig. 2). This approach offers both environmental and economic benefits.

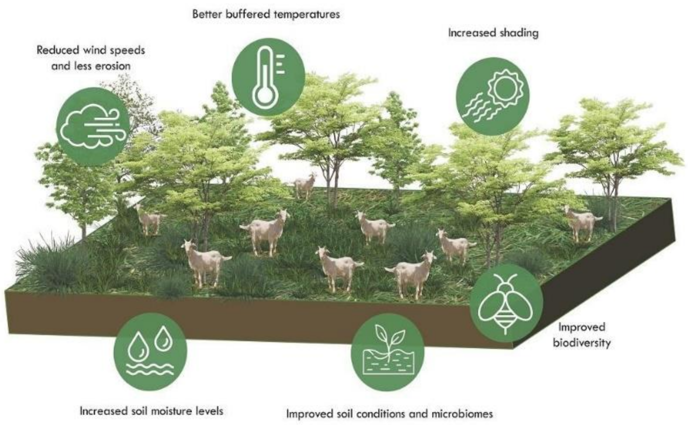

Fig. 2: Silvopastoral systems (Source: Insights Editor, 2023)

Historical perspective: Silvopastoral systems have been practiced for centuries in various forms around the world. Indigenous communities, for instance, have traditionally combined agroforestry with livestock grazing. These systems became a focal point for research and development in the late 20th century when the agroecological benefits were recognized.

Economic benefits: Silvopastoral systems offer numerous economic benefits. They enhance livestock productivity by providing shade and forage, leading to increased meat and milk production. The trees in these systems can also yield timber and non-timber forest products, providing additional income streams. Moreover, the presence of trees can enhance the aesthetic value of the land, potentially attracting ecotourism, further boosting the local economy.

2.3.3 Agroforestry approaches

Definition and overview: Agroforestry is a land use management system that integrates trees or shrubs with crops or livestock, or both. It is a deliberate effort to combine agricultural and forestry practices to achieve mutual benefits. The trees may be planted in rows, on borders, or in scattered patterns within crop fields or pastures.

Historical perspective: Agroforestry practices have a rich history, with traditional agroforestry systems found in various cultures worldwide. These systems were often born out of necessity to make the most of limited resources and enhance sustainability.

Economic benefits: Agroforestry approaches provide many economic advantages. They can improve soil fertility, which, in turn, boosts crop yields and reduces the need for synthetic fertilizers. The presence of trees can diversify income sources for farmers, as they can harvest tree products like fruits, nuts, and timber, in addition to their primary crops and livestock (Mishra, 2025). Agroforestry systems are also beneficial for carbon sequestration and can provide potential income through carbon credit markets, offering an additional economic incentive.

2.4 Benefits and challenges of dual production

Dual production refers to the integrated land management practice of combining agricultural crop production with livestock grazing on the same land. This approach aims to maximize land utility and enhance overall sustainability. It offers various benefits and also poses several challenges, making it a complex but valuable strategy for sustainable NRM. Let's explore the advantages and drawbacks of dual production:

Table 2: Benefits and challenges of dual production, with examples

S. No.	Benefits	Examples	Challenges	Examples
1.	Increased land-use efficiency	Farmers can use the same land to produce both crops and livestock, which can increase their overall productivity.	Overgrazing can lead to soil degradation, which can reduce crop yields and make it more difficult to grow plants.	Overgrazing can also reduce biodiversity and increase the risk of soil erosion.
2.	Improved soil fertility	Livestock manure can be used to fertilize crops, which can improve soil health and increase crop yields.	Livestock can spread diseases to crops, such as E. coli and salmonella.	This can make crops unsafe to eat and reduce their value.
3.	Reduced weed pressure	Livestock can graze on weeds, which can help to reduce weed pressure on crops.	Livestock can trample crops, which can damage or kill them.	This can reduce crop yields and increase the cost of production.
4.	Increased biodiversity	Dual production systems can support a wider range of plants and animals than monoculture systems.	Livestock can compete with wildlife for food and water.	This can lead to the decline of wildlife populations and reduce the overall resilience of the ecosystem.
5.	Reduced reliance on external inputs	Dual production systems can reduce the need for external inputs, such as fertilizer and pesticides.	Livestock can pollute waterways with manure and runoff from feedlots.	This can contaminate drinking water and harm aquatic ecosystems.

6.	Increased income for farmers	Dual production systems can provide farmers with a more diversified income stream.	Dual production systems can be more complex to manage than monoculture systems.	This can require farmers to have additional skills and knowledge.
7.	Improved animal welfare	Dual production systems can allow animals to graze on pasture, which can improve their welfare.	Dual production systems may require more labour than monoculture systems.	This can increase the cost of production and make it more difficult for farmers to find workers.
8.	Increased food security	Dual production systems can help to increase food security by providing a variety of food sources.	Dual production systems may be more vulnerable to climate change than monoculture systems.	This is because dual production systems often rely on rainfall and other climate-sensitive factors.

Dual production can offer a number of benefits, including increased land-use efficiency, improved soil fertility, reduced weed pressure, increased biodiversity, reduced reliance on external inputs, increased income for farmers, improved animal welfare, and increased food security. However, there are also some challenges associated with dual production, such as overgrazing, disease transmission, crop trampling, competition with wildlife, water pollution, increased complexity and labour requirements, and vulnerability to climate change (Bernues *et al.*,2011). Dual production is an ancient concept that has evolved to meet the demands of modern agriculture while maintaining a focus on sustainability and resource efficiency. This historical perspective underscores the enduring value of integrating crop cultivation and livestock grazing for more sustainable NRM (Tiwari *et al.*,2023).

3. Livestock Grazing in NRM

Livestock grazing plays a pivotal role in sustainable NRM. It involves the controlled consumption of vegetation by domestic animals like cattle, sheep, and goats, within a specific ecosystem. This practice has a long history and offers various economic, environmental, and social benefits when managed effectively.

3.1 Role of grazing in sustainable agriculture

Livestock grazing is an integral component of sustainable agriculture for many reasons:

- **Vegetation management:** Grazing helps control vegetation growth, preventing the dominance of certain plant species and promoting biodiversity. It reduces the accumulation of dry grasses, minimizing the risk of wildfires.

- **Nutrient cycling:** Grazing animals recycle nutrients through their dung and urine, enhancing soil fertility and nutrient availability for plant growth.
- **Soil health:** Light to moderate grazing can improve soil structure and reduce erosion by preventing overgrazing and soil compaction.
- **Weed control:** Grazing can be used to manage invasive species and noxious weeds, reducing the need for chemical herbicides.
- **Diversification:** Integrating livestock with crop farming diversifies income sources for farmers and reduces their dependence on a single revenue stream.
- **Carbon sequestration:** Well-managed grazing systems can contribute to carbon sequestration in grasslands, aiding in climate change mitigation.
- **Economic sustainability:** Livestock provide a source of income for farmers, both through the sale of meat and dairy products and through diversification into value-added products like wool and leather.

3.2 Grazing systems

There are several grazing systems employed in NRM, each with its own set of practices and benefits. These systems vary in their approach to managing livestock and vegetation. The choice of system depends on factors like the type of livestock, the local environment, and the specific goals of land management.

3.2.1 Rotational grazing

Rotational grazing is a strategic approach that divides a pasture into smaller sections or paddocks. Livestock are rotated among these paddocks, allowing each one to rest and regenerate while others are grazed (Fig. 3 and 4).

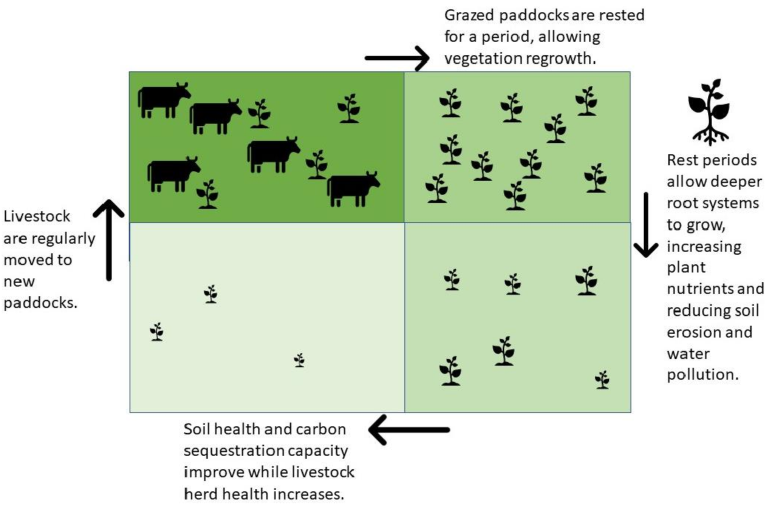

Fig. 3: Rotational grazing (Source: USDA Climate Hubs, n.d.)

This system offers many advantages:

- **Improved forage utilization:** Rotational grazing maximizes the use of available forage by preventing overgrazing and allowing forage to recover.

- **Reduced soil compaction:** The reduced stocking density in each paddock minimizes soil compaction.
- **Enhanced plant and soil health:** Plants have time to recover and grow, improving overall ecosystem health.
- **Increased carrying capacity:** The system often allows for more livestock on the same land area.

3.2.2 Continuous grazing

Continuous grazing involves allowing livestock to have access to a pasture or range without subdivision (Fig. 4). This system is less intensive than rotational grazing and is more suitable for extensive grazing operations.

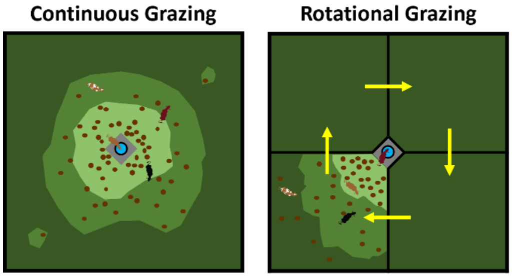

Fig. 4: Continuous and rotational grazing system

Some benefits of continuous grazing include:

- **Simplicity and low labour requirements:** Continuous grazing is easier to manage compared to rotational systems.
- **Lower infrastructure costs:** There is no need for fencing and paddock management.
- **Greater adaptability to specific environments:** In some cases, continuous grazing may be the most appropriate approach.

3.2.3 Adaptive grazing management

Adaptive grazing management is a flexible approach that adjusts grazing strategies based on changing conditions, such as weather, forage availability, and animal behaviour. Some elements of this system include:

- **Monitoring and data collection:** Regular assessment of forage conditions, livestock behaviour, and environmental factors.
- **Quick response to changing conditions:** Managers can adjust stocking rates, timing, and duration of grazing to optimize resource use.
- **Improved resilience:** Adaptive management helps land managers adapt to changing climate and environmental conditions.

Table 3: Comparison of rotational, continuous and adaptive grazing management

S. No.	Aspect	Continuous grazing	Rotation grazing	Adaptive grazing
1.	Grazing system	Continuous	Cyclic	Flexible
2.	Stocking density control	Low control	High control	Variable control
3.	Pasture utilization	Variable	High	Optimal
4.	Grazing period length	Continuous	Short intervals	Variable
5.	Grazing flexibility	Limited	Limited	High
6.	Pasture regeneration	Variable	Enhanced	Enhanced
7.	Forage health	Variable	Improved	Improved
8.	Labour intensity	Low	Moderate	Moderate to High
9.	Infrastructure requirement	Minimal	Fencing required	Variable
10.	Environmental impact	Variable	Managed	Managed
11.	Grazing efficiency	Low	High	Variable
12.	Response to Weather	N/A	Limited	Flexible

Source: Author's compilation

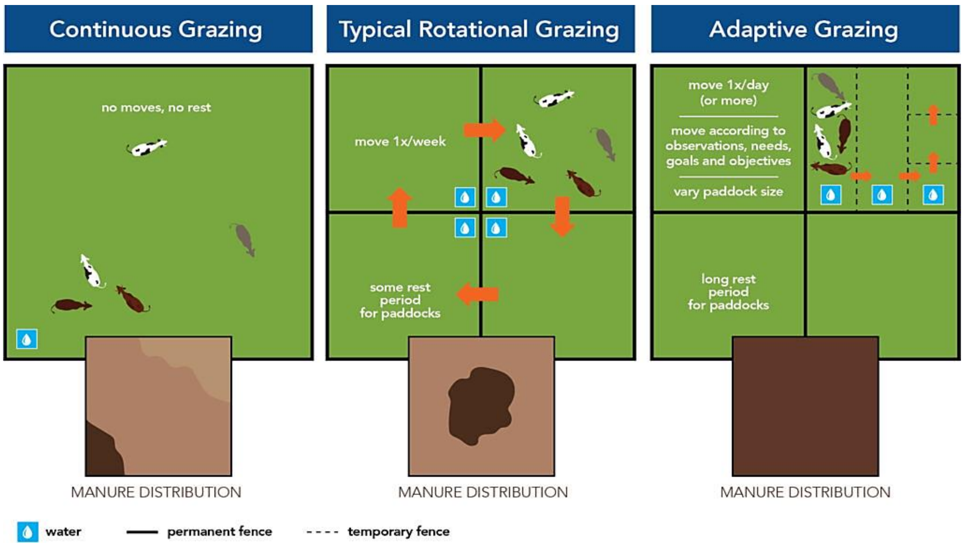

Fig. 5: Different grazing systems (Source: Pasture Project: Grazing Diagrams, n.d.)

Note: These are general characteristics, and the actual implementation and effectiveness of these grazing management practices may vary depending on specific circumstances and goals.

3.3 Environmental impacts of livestock grazing

Livestock grazing is a common practice worldwide and has significant implications for NRM, especially in terms of its environmental impacts. While grazing can provide economic benefits and support sustainable agriculture, it can also lead to various environmental challenges.

Understanding these impacts is crucial for designing effective management strategies that balance economic benefits with environmental conservation.

1. **Overgrazing:** One of the primary environmental concerns associated with livestock grazing is overgrazing. When there are too many animals in a given area, they can consume vegetation faster than it can regenerate. This leads to soil erosion, reduced plant diversity, and can negatively impact the habitat for native species. Overgrazing can also degrade soil quality, making it less able to support healthy vegetation growth.
2. **Soil erosion:** The trampling of hooves and removal of vegetation by grazing animals can contribute to soil erosion. This is particularly problematic in areas with steep terrain or fragile soils. Erosion can lead to sedimentation in nearby water bodies, affecting water quality and aquatic ecosystems.
3. **Water quality and riparian zones:** Livestock often congregate around water sources, leading to water quality issues. Their waste can contaminate streams, rivers, and ponds, affecting aquatic life and making the water less suitable for consumption. Additionally, the trampling and grazing of riparian zones (areas near water bodies) can damage vegetation, leading to soil erosion and reduced water quality.
4. **Biodiversity loss:** Intensive grazing can reduce plant diversity, making it difficult for native species to thrive. Non-native invasive species may take advantage of the disturbed environment, further threatening native flora and fauna. Maintaining biodiversity is essential for ecosystem resilience and health.
5. **Habitat alteration:** The presence of livestock can alter natural habitats. Grazing animals may trample or consume the vegetation that wildlife rely on for food and shelter. This can lead to habitat degradation and negatively impact local wildlife populations (Mishra, 2025).
6. **Nutrient cycling:** Livestock excrement can alter nutrient cycling in ecosystems. While some nutrients may enrich the soil, excessive nutrients, such as nitrogen and phosphorus, can lead to water pollution and eutrophication in nearby bodies of water, which can harm aquatic ecosystems.
7. **Fencing and infrastructure:** In some cases, fencing and other infrastructure associated with livestock grazing can disrupt natural habitats and migration patterns of wildlife. These barriers can limit the movement of animals and exacerbate fragmentation of ecosystems.
8. **Mitigation strategies:** To minimize the environmental impacts of livestock grazing, various strategies can be employed, such as rotational grazing, where animals are moved to different pastures to prevent overgrazing in a single area. Implementing riparian buffers, which are areas with native vegetation around water bodies, can help protect

water quality. Employing sustainable grazing practices, setting appropriate stocking rates, and monitoring the health of ecosystems are major components of responsible NRM.

While livestock grazing is an essential component of dual production for sustainable NRM, it must be managed carefully to mitigate its environmental impacts. Balancing the economic benefits of grazing with the conservation of ecosystems and wildlife is crucial for achieving long-term sustainability.

3.4 The economics of grazing

Grazing livestock play a vital role in the global economy, contributing to food security, rural livelihoods, and ecosystem services. In 2020, the global livestock sector generated an estimated $1.4 trillion in gross value added (GVA), accounting for 4.1% of global agricultural GVA. Livestock grazing also supports over 1 billion livelihoods worldwide, the majority of whom are smallholder farmers in developing countries. In recent years, the global livestock sector has undergone a significant transformation, driven by rising incomes, urbanization, and changing dietary patterns (Benjaminsen and Bryceson, 2012). This has led to an increase in the demand for livestock products, particularly meat and dairy. However, the sector has also faced increasing scrutiny for its environmental and social impacts. One of the major challenges facing the global livestock sector is the need to produce more food with less environmental impact. Grazing livestock can play a role in meeting this challenge, as they can help to improve soil health, reduce water pollution, and sequester carbon. However, it is important to manage grazing sustainably to avoid negative impacts such as overgrazing, land degradation, and biodiversity loss. India is home to the world's largest livestock population, with over 303.76 million bovines (cattle, buffalo, mithun and yak), 74.26 million sheep, 148.88 million goats, 9.06 million pigs and about 851.81 million poultry as per 20th Livestock Census in the country. Livestock grazing plays a vital role in the Indian economy, contributing around 4.5% of GDP and supporting over 100 million livelihoods. Despite these challenges, the Indian livestock sector has the potential to play a major role in the country's economic development. However, this will require significant investment in improving the efficiency and sustainability of production systems. Livestock grazing has a significant impact on the economic dynamics of agricultural and NRM systems. The economics of grazing involves the analysis of the costs, benefits, and overall financial implications associated with integrating livestock grazing into NRM strategies (Gerber *et al.*,2015). This assessment encompasses a range of factors, including the direct and indirect costs of grazing, the market value of the livestock, the impact on the surrounding ecosystem, and the potential for generating income through dual production.

3.4.1 Some aspects of the economics of grazing

Cost-benefit analysis: Conducting a comprehensive cost-benefit analysis is essential to evaluate the financial viability of incorporating livestock grazing into NRM. This analysis should consider the expenses related to maintaining grazing areas, managing livestock, providing necessary infrastructure, and mitigating any environmental degradation caused by overgrazing. Simultaneously, it should weigh the benefits in terms of increased land productivity, improved soil fertility, and potential revenue from livestock products.

Market value of livestock products: Assessing the market value of livestock products, such as meat, milk, and wool, is crucial in understanding the potential economic returns of livestock grazing. This evaluation involves considering market trends, consumer demand, and pricing fluctuations to determine the profitability of engaging in livestock production alongside grazing activities. Moreover, exploring value-added opportunities, such as organic or premium product markets, can enhance the economic benefits of livestock grazing.

Ecological impact and externalities: Recognizing the ecological impact and externalities associated with livestock grazing is essential for accurately accounting for the true costs of this practice. Factors such as soil erosion, water contamination, and habitat degradation should be quantified in economic terms to understand the long-term consequences and external costs incurred by livestock grazing. Implementing sustainable grazing practices that minimize these negative externalities can help improve the overall economic sustainability of NRM systems.

Integrated management approaches: Emphasizing integrated management approaches that combine livestock grazing with sustainable agriculture or conservation practices can enhance the economic resilience of NRM systems. This involves implementing rotational grazing techniques, incorporating agroforestry systems, and promoting biodiversity conservation to create synergies that improve overall resource productivity and financial returns.

3.4.2 Key concepts

- **Carrying capacity (CC):** The carrying capacity of a grazing area refers to the maximum number of livestock that can be sustained by the available forage throughout the year without degrading the ecosystem. It is typically measured in Animal Unit Months (AUM), representing the forage required by one animal unit (usually a cow and calf pair) for one month.
- **Grazing intensity:** This is the number of animals actually present on a grazing area relative to its carrying capacity. Proper management aims to maintain a sustainable grazing intensity to prevent overgrazing, which can lead to resource degradation.
- **Stocking rate:** The stocking rate is the number of livestock units (e.g., cows, sheep, or goats) on a specific grazing area. It is a critical parameter in determining the economic viability of livestock grazing.
- **Gross income:** Gross income in grazing refers to the revenue generated from livestock sales. It depends on the number of animals and their market value.
  Gross income (GI): GI = Number of livestock × Market value per head
- **Operating costs:** These include expenses related to livestock management, such as feed, labour, veterinary care, and infrastructure maintenance.

Operating costs (OC): OC = Cost per animal unit × Number of animal units

- **Net income:** Net income is the difference between gross income and operating costs. It is a crucial indicator of the economic profitability of livestock grazing.

  Net income (NI): NI = Gross income - Operating costs

3.4.3 Practical examples

Let's consider a practical example of a cattle ranch in the southwestern United States, which has a carrying capacity of 1,000 Animal Unit Months (AUMs) for cattle. The rancher has 500 cow-calf pairs and plans to graze them for six months. Each cow-calf pair has a market value of $1,200, and the cost per AUM is $50.

Gross income: GI = 500 cow-calf pairs × $1,200 per pair = $600,000

Operating costs: OC = $50 per AUM × (500 cow-calf pairs × 6 months) = $150,000

Net income: NI = $600,000 (Gross Income) - $150,000 (Operating Costs) = $450,000

In this example, the rancher would earn a net income of $450,000 from grazing. This demonstrates the potential economic benefits of sustainable livestock grazing when carried out at an appropriate stocking rate and within the carrying capacity of the land.

These formulas and examples illustrate how the economics of grazing can be calculated to assess the financial viability of livestock operations. Sustainable livestock grazing, when managed correctly, can generate significant economic benefits while preserving the health and productivity of natural resources. It is essential for ranchers and land managers to strike a balance between economic profitability and environmental conservation in the pursuit of dual production and sustainable NRM (Nishad *et al.*,2023).

4. Economic Benefits of Dual Production

In the context of sustainable NRM, dual production refers to the integrated practice of combining both agriculture (crop cultivation) and livestock grazing within the same land area. This approach offers a range of economic benefits that not only improve the financial sustainability of agricultural operations but also contribute to overall environmental sustainability. Here, we will discuss some economic advantages of dual production:

4.1 Increased productivity and efficiency

Dual production systems can significantly enhance productivity and operational efficiency in agriculture and livestock sectors. Here are some major points to consider:

1. **Improved nutrient cycling:** In a dual production system, the integration of crop farming and livestock grazing can lead to better nutrient cycling. Livestock can graze on crop residues, cover crops, or pastures, and their manure can serve as a valuable source of organic fertilizer. This reduces the need for synthetic fertilizers in crop farming, lowering input costs and enhancing soil fertility. As a result, crop yields tend to be higher, and livestock can thrive on more nutritious forage.

2. **Reduced pest and weed pressure:** The diverse landscape in dual production systems can disrupt pest and weed cycles. Livestock grazing can help control weed populations, while crop rotations can reduce the buildup of specific pests. This minimizes the need for chemical pesticides and herbicides, reducing production costs and potentially improving crop quality.
3. **Enhanced soil health:** Dual production practices, such as rotational grazing and cover cropping, promote soil health and reduce erosion. Healthy soils lead to better water retention and improved crop yields, all while requiring fewer inputs like irrigation and soil amendments.
4. **Increased labour efficiency:** Dual production allows farmers to make more efficient use of their labour force. Activities such as feeding livestock, spreading manure, and managing pasture rotations can be integrated with crop farming operations. This reduces the need for additional labour and can lead to cost savings.

4.2 Diversified income streams

Diversification is a key principle in economic risk management, and dual production provides an opportunity to diversify income streams. Here are some aspects of this economic benefit:

1. **Stable cash flow:** Dual production systems typically involve multiple sources of income. Farmers can generate revenue from both crop sales and livestock production, which may include meat, milk, or fiber. This diversification helps stabilize cash flow throughout the year, as crop and livestock sales often have different harvest and market periods.
2. **Risk mitigation:** Agriculture is vulnerable to various risks, including weather-related disasters, market fluctuations, and disease outbreaks. Dual production spreads these risks across two or more sectors, reducing the impact of adverse events on overall income. For example, if a crop fails due to adverse weather, livestock sales can provide a safety net, and vice versa.
3. **Added value products:** In a dual production system, there may be opportunities to create value-added products, such as processed foods, specialty crops, or artisanal livestock products. These can command higher prices in niche markets, further increasing income potential.
4. **Cost savings:** Dual production can also lead to cost savings through shared infrastructure and resources. For example, the same land, barns, and equipment can be used for both crop and livestock operations, reducing the capital and maintenance expenses associated with operating separate enterprises.

4.3 Resource optimization

Resource optimization is a central economic benefit of dual production. By combining crop cultivation and livestock grazing on the same land, farmers can maximize the use of available resources such as land, water, and nutrients. Here's how resource optimization works:

1. **Land use efficiency**: Dual production allows farmers to efficiently utilize their land. While crops are grown on the field, animals can graze on the same land or in adjacent pastures. This land-sharing approach reduces the need for extensive grazing areas and prevents overgrazing in a particular location. As a result, the land's carrying capacity can be fully realized.
2. **Nutrient cycling**: The integration of crop and livestock systems promotes the efficient cycling of nutrients. Animal waste can serve as a natural fertilizer for crops, reducing the need for synthetic fertilizers. This not only cuts down on input costs (as discussed in section 4.4) but also minimizes the risk of nutrient runoff into nearby water bodies, thus contributing to environmental conservation.
3. **Water management**: Dual production allows for improved water management. Livestock and crops can be strategically rotated on the land, reducing soil erosion and optimizing water use. In areas with limited water resources, this practice can be particularly valuable as it ensures that both crops and animals have access to sufficient water without depleting local water sources.

4.4 Reduced input costs

One of the most compelling economic benefits of dual production is the reduction of input costs for farmers. This is achieved through several means:

1. **Fertilizer savings**: As mentioned earlier, integrating livestock into crop production systems allows for the use of animal manure as a natural fertilizer. This reduces the need for synthetic fertilizers, which can be expensive. Additionally, manure improves soil structure and organic matter, leading to healthier and more productive soils.
2. **Pest and weed control**: Livestock, such as chickens or goats, can be used to control weeds and pests in agricultural fields. This reduces the need for chemical pesticides, which not only saves money but also promotes environmentally friendly farming practices.
3. **Feed production**: By allowing livestock to graze on crop residues or cover crops after the primary crop is harvested, farmers can reduce the cost of animal feed. This can significantly cut down on the expenses associated with livestock husbandry.

4.5 Market opportunities and value addition

The integration of dual production can create valuable market opportunities and enhance the economic viability of farming operations:

1. **Diversified income streams**: Dual production provides farmers with multiple income streams. They can generate revenue from both crop sales and livestock products (meat, milk, eggs) or even non-food products (e.g., wool or leather). This diversification of income sources can help stabilize a farmer's financial situation and reduce dependence on a single market.

2. **Value addition**: The combination of crops and livestock opens the door to value addition opportunities. For instance, farmers can process their agricultural products and animal products into higher-value goods like cheese, jams, or organic meat. Value-added products often command higher prices in the market, leading to increased profitability.
3. **Market demand for sustainability**: In recent years, there has been a growing consumer demand for sustainable and environmentally friendly products. Dual production systems align well with these trends, allowing farmers to market their products as more sustainable and ecologically responsible, often at a premium price.

Dual production is a sustainable agricultural practice that offers a range of economic benefits. It enhances productivity, diversifies income, optimizes resource use, reduces input costs, and creates market opportunities with value addition. By adopting dual production, farmers can improve their economic resilience and contribute to sustainable NRM (Kaswamila, 2012; Mishra, 2024).

5. Economic Analysis Methods

Economic analysis is a crucial component when evaluating the benefits of dual production and livestock grazing for sustainable NRM. This section will discuss various economic analysis methods, including Cost-Benefit Analysis (CBA), Return on Investment (ROI), Profitability Metrics, and Long-term Economic Sustainability. We will provide definitions, formulas, implications, and examples for each of these methods.

5.1 Cost-Benefit Analysis (CBA)

Definition and overview: Cost-Benefit Analysis (CBA) is a systematic approach used to evaluate and compare the total costs and benefits of a particular project, policy, or activity. In the context of dual production and livestock grazing, CBA can help assess whether the economic benefits exceed the associated costs, making it an essential tool for decision-makers. The fundamental formula for CBA involves subtracting the total costs from the total benefits to determine the net benefit (NB):

$$\text{Net Benefit (NB)} = \text{Total Benefits} - \text{Total Costs}$$

Implications:

- If $NB > 0$, the project is considered economically viable, indicating that the benefits outweigh the costs.
- If $NB < 0$, the project is economically unviable and may need re-evaluation or reconsideration.
- CBA allows for the comparison of different projects and helps in selecting the one that offers the highest net benefit.

Example: Suppose you are considering the implementation of a dual production system that involves cultivating crops and allowing livestock grazing on your land. You calculate the total benefits, including increased crop yields and income from livestock, and the total costs, including investment in fencing and livestock maintenance. If the net benefit is positive, it suggests that the dual production system is economically beneficial.

5.2 Return On Investment (ROI)

Definition and overview: Return on Investment (ROI) is a financial metric used to assess the efficiency and profitability of an investment or project. In the context of dual production and livestock grazing, ROI can help determine how effectively resources are utilized and the rate at which they generate returns. The formula for calculating ROI is as follows:

$$\boldsymbol{ROI}\ (\%) = \left[\frac{Net\ Profit}{Initial\ Investment}\right] \times 100$$

Implications:

- A higher ROI indicates a more profitable project.
- ROI can be used to compare the returns on different projects, helping in the allocation of resources.
- A positive ROI is generally desirable, but the benchmark for an acceptable ROI may vary depending on the context and industry.

Example: Let's say you invest $10,000 in setting up a dual production system involving both crops and livestock. Over the year, you generate a net profit of $3,000. Using the ROI formula, you calculate a return of 30%. This means that for every dollar invested, you are earning 30 cents in profit, which is a positive indicator for your project's profitability.

5.3 Profitability metrics

Definition and overview: Profitability metrics encompass various financial indicators that evaluate the profitability of a project or business. In the context of dual production and livestock grazing, some profitability metrics include Gross Profit Margin, Net Profit Margin, and Break-Even Point.

$$Gross\ Profit\ Margin\ (\%) = \left[\frac{Gross\ Profit}{Total\ Revenue}\right] \times 100$$

$$Net\ Profit\ Margin\ (\%) = \left[\frac{Net\ Profit}{Total\ Revenue}\right] \times 100$$

$$Break - Even\ Point = \frac{Fixed\ costs}{(Selling\ price\ per\ unit - Variable\ costs\ per\ unit)}$$

Implications:

- Gross Profit Margin measures the profitability of a project before accounting for indirect costs.
- Net Profit Margin considers all costs and provides insight into the overall profitability.
- Break-Even Point helps determine the level of sales required to cover all costs, beyond which the project starts generating profit.

Example: Suppose you have a dual production and livestock grazing project. Your total revenue for the year is $50,000, and your gross profit is $20,000. Using the Gross Profit Margin formula, you find that your gross profit margin is 40%. This indicates that 40% of your revenue is retained as profit before accounting for indirect costs.

5.4 Long-term economic sustainability

Definition and overview: Long-term economic sustainability assesses the ability of a project, such as dual production and livestock grazing, to maintain economic benefits over an extended period. It considers factors like resource conservation, environmental impacts, and adaptability to changing market conditions.

Implications:

- Sustainable practices ensure that natural resources are conserved, reducing long-term costs and enhancing resilience against market fluctuations.
- A project demonstrating long-term economic sustainability is more likely to contribute positively to the environment and local communities.

Example: For long-term economic sustainability in dual production and livestock grazing, you may adopt practices such as crop rotation to maintain soil health, responsible livestock grazing management to prevent overgrazing, and the use of drought-resistant crops. These strategies help ensure that the project remains economically viable and environmentally sustainable in the long run.

These economic analysis methods and concepts are essential for evaluating the economic benefits of dual production and livestock grazing for sustainable NRM (Mishra, 2024). They provide tools to make informed decisions, allocate resources effectively, and assess the long-term viability of such projects.

Conclusion:

Dual production and livestock grazing present a sustainable strategy for NRM in modern agriculture. Integrating crops and livestock through systems like silvopasture and agroforestry enhances productivity while promoting environmental stewardship. Livestock grazing—when managed through rotational, continuous, or adaptive systems—can support pasture health and land use efficiency, though it requires careful oversight to mitigate environmental impacts. Economically, dual production offers substantial benefits including increased productivity, diversified income, reduced input costs, and greater market opportunities. Analytical tools like cost-benefit analysis and return on investment are vital for assessing long-term sustainability and guiding informed decisions. Policy frameworks, including government incentives and sustainability standards, are essential to encourage adoption, while land use planning supports efficient resource allocation. Despite these benefits, challenges remain—balancing crop and livestock demands, conserving biodiversity, managing markets, and addressing climate change impacts. However, these challenges also offer opportunities for innovation and resilience. Advancements in technology, precision agriculture, and research will be key to refining these integrated systems. As global demand for sustainable agriculture rises, embracing dual production and responsible grazing can pave the way for a resilient, productive, and economically viable agricultural future.

References:

1. Bellamy, J. A., Walker, D. H., McDonald, G. T., & Syme, G. J. (2001). A systems approach to the evaluation of natural resource management initiatives. *Journal of environmental management*, *63*(4), 407-423, DOI: 10.1006/jema.2001.0493.
2. Benjaminsen, T. A., & Bryceson, I. (2012). Conservation, green/blue grabbing and accumulation by dispossession in Tanzania. *Journal of Peasant Studies*, *39*(2), 335-355, DOI: 10.1080/03066150.2012.667405.
3. Bernués, A., Ruiz, R., Olaizola, A., Villalba, D., & Casasús, I. (2011). Sustainability of pasture-based livestock farming systems in the European Mediterranean context: Synergies and trade-offs. *Livestock Science*, *139*(1-2), 44-57, DOI: 10.1016/j.livsci.2011.03.018.
4. Burark, S. S., Varghese, K. A., & Varghese, N. (2023). Sustainable Natural Resource Management in Thar Desert-Way Ahead. In *Natural Resource Management in the Thar Desert Region of Rajasthan* (pp. 329-342). Cham: Springer International Publishing, DOI: 10.1007/978-3-031-34556-2_14.
5. Chapin III, F. S., Kofinas, G. P., & Folke, C. (Eds.). (2009). *Principles of ecosystem stewardship: resilience-based natural resource management in a changing world*. Springer Science & Business Media.
6. Devendra, C. (2011). Integrated tree crops-ruminants systems in South East Asia: Advances in productivity enhancement and environmental sustainability. *Asian-Australasian Journal of Animal Sciences*, *24*(5), 587-602, DOI: 10.5713/ajas.2011.r.07.
7. Devendra, C., & Chantalakhana, C. (2002). Animals, poor people and food insecurity: opportunities for improved livelihoods through efficient natural resource management. *Outlook on Agriculture*, *31*(3), 161-175, DOI: 10.5367/000000002101294010.
8. Dixon, A. B., & Wood, A. P. (2003, May). Wetland cultivation and hydrological management in eastern Africa: Matching community and hydrological needs through sustainable wetland use. In *Natural resources forum* (Vol. 27, No. 2, pp. 117-129). Oxford, UK: Blackwell Publishing Ltd, DOI: 10.1111/1477-8947.00047.
9. Dumont, B., Fortun-Lamothe, L., Jouven, M., Thomas, M., & Tichit, M. (2013). Prospects from agroecology and industrial ecology for animal production in the 21st century. *animal*, *7*(6), 1028-1043, DOI: 10.1017/S1751731112002418.
10. FAO (2015). Dual production systems: A pathway to sustainable food security. Rome, Italy: Food and Agriculture Organization of the United Nations.

11. Farina, A. (2000). The cultural landscape as a model for the integration of ecology and economics. *BioScience*, *50*(4), 313-320, DOI: 10.1641/0006-3568(2000)050[0313:TCLAAM]2.3.CO;2.
12. Franzluebbers, A. J. (2007). Integrated crop–livestock systems in the southeastern USA, DOI: 10.2134/agronj2006.0076.
13. Gerber, P. J., Mottet, A., Opio, C. I., Falcucci, A., & Teillard, F. (2015). Environmental impacts of beef production: Review of challenges and perspectives for durability. *Meat science*, *109*, 2-12, DOI: 10.1016/j.meatsci.2015.05.013.
14. Herrero, M., Grace, D., Njuki, J., Johnson, N., Enahoro, D., Silvestri, S., & Rufino, M. C. (2013). The roles of livestock in developing countries. *animal*, *7*(s1) (Supplement 1), 3-18, DOI: 10.1017/S1751731112001954.
15. Insights Editor. (2023, July 26). *Silvopasture systems* - Insightsias. https://www.insightsonindia.com/2023/07/26/silvopasture-systems/
16. Jones, B., & Murphree, M. W. (2013). Community-based natural resource management as a conservation mechanism: Lessons and directions. In *Parks in transition* (pp. 63-103). Routledge.
17. Jose, S., & Dollinger, J. (2019). Silvopasture: a sustainable livestock production system. *Agroforestry systems*, *93*, 1-9, DOI: 10.1007/s10457-019-00366-8.
18. Kangalawe, R. Y., & Liwenga, E. T. (2005). Livelihoods in the wetlands of Kilombero Valley in Tanzania: Opportunities and challenges to integrated water resource management. *Physics and Chemistry of the Earth, Parts A/B/C*, *30*(11-16), 968-975, DOI: 10.1016/j.pce.2005.08.044.
19. Kaswamila, A. (2012). An analysis of the contribution of community wildlife management areas on livelihood in Tanzania. *Sustainable natural resources management*, 139-54, DOI: 10.5772/32987.
20. Kellert, S. R., Mehta, J. N., Ebbin, S. A., & Lichtenfeld, L. L. (2000). Community natural resource management: promise, rhetoric, and reality. *Society & Natural Resources*, *13*(8), 705-715, DOI: 10.1080/089419200750035575.
21. Kumar, N., Kushwaha, R. R., Meena, N. R., Mishra, H., & Yadav, A. P. S. (2023). A study on costs and returns of paddy cultivation in Ambedkar Nagar district of Uttar Pradesh. *International Journal of Statistics and Applied Mathematics*, SP-83: 107-111.
22. Li, X. L., Yuan, Q. H., Wan, L. Q., & He, F. (2008). Perspectives on livestock production systems in China. *The Rangeland Journal*, *30*(2), 211-220, DOI: 10.1071/RJ08011.
23. Mishra, H. (2024). Nanobiostimulants and Precision Agriculture: A Data-Driven Approach to Farming and Market Dynamics. In *Nanobiostimulants: Emerging Strategies for Agricultural Sustainability* (pp. 365-398). Cham: Springer Nature Switzerland, DOI: 10.1007/978-3-031-68138-7_16.

24. Mishra, H. (2024). The Role of Ethnoeconomics in Promoting Sustainable Consumption and Production Patterns: A Pathway to Environmental Protection and Economic Prosperity. *Sustainable Development*. In *Seen Through the Lenses of Ethnoeconomics and the Circular Economy* (pp. 91-123). Cham: Springer Nature Switzerland, DOI: 10.1007/978-3-031-72676-7_6.
25. Mishra, H. (2025). Artificial Intelligence, Machine Learning and IoT Integration in Agriculture: A Review. *Journal of Science Research International*, *11*(1), 110-127.
26. Mishra, H. (2025). Environmental Degradation and Impacts on Agricultural Production: A Challenge to Urban Sustainability. In *Sustainable Urban Environment and Waste Management: Theory and Practice* (pp. 53-92). Singapore: Springer Nature Singapore, DOI: 10.1007/978-981-96-1140-9_3.
27. Mishra, H. (2025). Strategies for Achieving Free Trade and Removing Barriers to the Movement of Goods and Services Within Integrated Economies. In *Economic Integration Strategies, Challenges and Global Implications* (pp. 91-113). Nova Science Publishers, Inc.
28. Mishra, H., & Mishra, D. (2024). AI for Data-Driven Decision-Making in Smart Agriculture: From Field to Farm Management. In *Artificial Intelligence Techniques in Smart Agriculture* (pp. 173-193). Singapore: Springer Nature Singapore, DOI: 10.1007/978-981-97-5878-4_11.
29. Mishra, H., & Mishra, D. (2024). Economic evaluation of UAV-based soil sampling approaches. In *Applications of Computer Vision and Drone Technology in Agriculture 4.0* (pp. 271-291). Singapore: Springer Nature Singapore, DOI: 10.1007/978-981-99-8684-2_15.
30. Mishra, H., & Mishra, D. (2024). Sustainable Smart Agriculture to Ensure Zero Hunger. In *Sustainable Development Goals* (pp. 16-37). CRC Press, DOI: 10.1201/9781003468257-2.
31. Mishra, H., & Mishra, D. (Eds.). (2023). Artificial Intelligence and Machine Learning in Agriculture: Transforming Farming Systems. In Research Trends in Agriculture Science (Volume I), 1-16. Bhumi Publishing.
32. Mishra, H., Tiwari, A. K., & Nishad, D. C. (2011). Economic viability of sustainable agriculture practices in modern farming. *Advances in Agriculture Sciences Volume II*, *24*(4), 105.
33. Nishad, D. C., Mishra, H., Tiwari, A. K., & Mishra, D. (2011). Post-harvest Management: Enhancing food security and sustainability. *Advances in Agriculture Sciences Volume II*, *24*(4), 136.

34. Nishad, D. C., Mishra, H., Tiwari, A. K., & Pandey, A. (Eds.) (2023). Towards Sustainable Agriculture: Mitigating the Adverse Effects of Stubble Burning in India. *Research Trends in Environmental Science* (Volume I, pp: 42-48). Bhumi Publishing.
35. *Pasture Project : Grazing diagrams.* (n.d.). https://pastureproject.org/publications/grazing-continuum-diagram/
36. Prasad, C. S., Anandan, S., Gowda, N. K., Schlecht, E., & Buerkert, A. (2019). Managing nutrient flows in Indian urban and peri-urban livestock systems. *Nutrient Cycling in Agroecosystems*, 115, 159-172, DOI: 10.1007/s10705-018-9964-0.
37. Reddy, P. P., & Reddy, P. P. (2016). Integrated crop–livestock farming systems. *Sustainable intensification of crop production*, 357-370, DOI: 10.1007/978-981-10-2702-4_23.
38. *Rotational grazing for climate resilience | USDA Climate Hubs*. (n.d.). https://www.climatehubs.usda.gov/hubs/international/topic/rotational-grazing-climate-resilience
39. Stone, L. S., & Stone, T. M. (2011). Community-based tourism enterprises: challenges and prospects for community participation; Khama Rhino Sanctuary Trust, Botswana. *Journal of Sustainable Tourism*, *19*(1), 97-114, DOI: 10.1080/09669582.2010.508527.
40. Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2853-2867, DOI: 10.1098/rstb.2010.0134.
41. Tiwari, A. K., Mishra, H., & Nishad, D. C. (2011). Market dynamics and consumer perceptions of organic produce in contemporary agriculture. *Advances in Agriculture Sciences Volume II*, *24*(4), 120.
42. Tiwari, A. K., Mishra, H., Nishad, D. C., & Pandey, A. (Eds.). (2023). Sustainable Water Management in Agriculture: Irrigation Techniques and Water Conservation (pp. 53-68). In Research Trends in Agriculture Science (Volume II). Bhumi Publishing.
43. Topp-Jørgensen, E., Poulsen, M. K., Lund, J. F., & Massao, J. F. (2005). Community-based monitoring of natural resource use and forest quality in montane forests and miombo woodlands of Tanzania. *Biodiversity & Conservation*, *14*, 2653-2677, DOI: 10.1007/s10531-005-8399-5.
44. Turner, R. K. (2004). *Economic valuation of water resources in agriculture: From the sectoral to a functional perspective of natural resource management* (Vol. 27). Food & Agriculture Org.

NOVEL EXTRACTIVE SPECTROPHOTOMETRIC DETERMINATION METHOD OF NICKEL (II)

Ghanasham Bhikaji Sathe

Dapoli Urban Bank Senior Science College, Dapoli, Maharashtra

Corresponding author E-mail: gbsathe47@gmail.com

Abstract:

2-[(E)-N-(2—{[2-[(E)-[(2-hydroxyphenyl) methylildene] amino] phenyl} (methyl) amino} phenyl) carboximidoyl] phenol (HHMCP) was synthesized and employed to develop an extractive spectrophotometric method for the determination of Ni (II). The reagent forms a complex with Ni (II) and can be quantitatively extracted in Chloroform at pH = 7.0. The extracted species showed an absorption maximum at 495 nm with molar absorptivity of 0.75 $\times 10^2$ L mol^{-1} cm^{-1}. A systematic study of the extraction was carried out by varying the parameters like pH, reagent concentration and equilibration time. The method has been successfully applied for the determination of Nickel in synthetic mixtures and alloy samples.

Keywords: HHMCP, Nickel (II), Extractive Spectrophotometric Determination, Solvent Extraction.

Introduction:

The significance of nickel as a transition metal lies in its wide spectrum of applications covering many frontier areas of study, particularly in industrial and consumer products. Even though nickel is not considered to be as toxic as most of the heavy metals, it is an equally harmful element. Hence, owing to the significance of nickel, it's determination from associated elements by extractive spectrophotometry has been of considerable importance. A wide variety of reagent has been reported for the spectrophotometric determination of nickel. However, these methods suffer from limitations such as critical pH [1-3], requirement of masking agent1 or other agents [4, 5], requirement of heating[6], and interference from some ions[1, 7] etc.

Nickel is widely used in electroplating, the manufacture of Ni-Cd batteries, rods for arc welding, pigments of paints, ceramic, surgical and dental prostheses, magnetic tapes and computer components and nickel catalysts. Nickel enters waters from dissolution of industrial processes and waste disposal [8]. Nickel was thought to be essential for plants and some domestic animals [9], but not considered to be a metal of biological importance until 1975, when Zerner discovered that urease was a nickel enzyme [10]. Nickel is essential constituent in plant urease. Jack beans and soybeans generally contain high concentration of nickel [8]. Compared with other transition metals, nickel is moderately toxic element, and still at low concentration produces a general toxic effect on the human organism, causing nasopharynx and lung diseases, malignant tumors and dermatological diseases [11]. Nickel-containing sewage is harmful after ingress into water. This fact explained the importance of the monitoring of nickel concentration in natural and waste water samples. Flame and graphite furnace atomic absorption spectrometry and spectrophotometric methods provides accurate and rapid determination of nickel in natural and waste waters [12]. However, very frequently a direct determination cannot be applied due to low concentration of analyte or matrix interferences.

The most widely used techniques for the separation and preconcentration of nickel are liquid-liquid extraction [13], precipitation [14], and chelating resin [15]. The large distribution ratios attainable in some solvent extraction systems allow the analytes determination at trace levels.

An advantage of solvent extraction is that both separation and preconcentration which are often required; can be obtained in the same step [16]. Historically the first instance of chemical analysis of metal ions was combination of liquid extraction and spectrophotometric methods, in which the analysis was performed on the extracting phase. Nevertheless, the solvent extraction of nickel is still an important process and is used in several plants to recover and separate nickel from wastewaters [17, 18]. Many classical ligands such as dimethylglyoxime, dithizone, and sodium-diethyldithiocarbamate are known as an extractant for extraction/spectrophotometric determination of nickel [19, 20].

In chemical analysis, metal chelation followed by solvent extraction and spectrophotometric detection is the preferred mode of analysis for a number of metal ions [21, 22] due to its rapidity, simplicity and wide applications. Several spectrophotometric methods have been developed in which the solvent extraction step is conveniently replaced by the use of a surfactant [23, 24].

Currently the interest in the preservation of the environment is increasing. The threshold concentrations for toxic species established by the environmental legislation have been continuously reduced and the detection limits of the analytical methodologies need to follow this trend. UV/Vis spectrophotometry is a mature analytical technique applied to many thousands of determinations owing to its simplicity, flexibility, low cost and convenience [25]. However, conventional UV/Vis spectrophotometry often presents detection limits incompatible to the requirements. Thus, alternatives have been investigated to increase sensitivity, such as formation of products with higher molar absorptivities [26], pre-concentration exploiting solid–liquid [27] or liquid–liquid [28] extraction, etc. Pre-concentration is the most usual approach, but it is time-consuming and often involves generation of toxic effluents such as organic solvents. At present, for to resolve these problems, a rich variety of greener methods have been developed to extract and concentrate analytes, such as ultrasound, microwave-assisted extraction, supercritical fluid extraction, superheated water extraction, membranes and cloud point extraction (CPE).

By means of CPE, the metals are extracted into micelles with a complexing agent in the presence of a surfactant. Above the critical micelle concentration, a separate phase is created [29]. This strategy has been used for sample clean up and mainly to concentrate the analyte or the reaction product before analysis, which can be carried out by several techniques, such as UV/Vis spectrophotometry, atomic spectrometry or capillary electrophoresis [30].

The CPE of metals, with spectrophotometric detection, was first reported by Watanabe and co-workers, who studied the preconcentration of Ni with 1-(2-thiazolylazo)-2-naphthol in Triton X-100 micellar solution [31], but this surfactant has a relatively high cloud point, around 70 ºC. Later, CPE was applied to other determinations of diverse ions, different of nickel, spectrophotometrically [32-49]. Nickel is a moderately toxic element compared to other transition metals. Environmental pollution monitoring requires determination of nickel in trace levels in various samples. Recently, numerous methods have been published on the preconcentration of nickel, alone or in mixtures, by CPE method prior to its determination using spectrometric techniques [50-65].

Materials and Experimental Methods:

Apparatus:

All absorbance measurements were made on Systronics Digital Double Beam spectrophotometer model-2101 with 1 cm quartz cell. Standard volumetric flasks, 125ml separatory funnels, beakers were used for volumetric measurements. All dilutions were made using double distilled water. Solvents like chloroform, ethanol were used after double distillation. All interfering ion solutions were prepared in double distilled water

Standard nickel solution:

A stock solution of Ni (II) was prepared by dissolving 1 g Nickel chloride hexahydrate in 250 ml double distilled water and standardized.[*] A working solution of 100µg/ml was prepared by dilution of the stock solution with double distilled water in a standard volumetric flask.

Standard reagent solution:

2-[(E)-N-(2—{[2-[(E)-[(2-hydroxyphenyl) methylildene] amino] phenyl} (methyl) amino} phenyl) carboximidoyl] phenol (HHMCP), (10^{-2}M) was always prepared by dissolving 0.478 g of HHMCP in 100 ml chloroform and used.

Recommended method:

To an aliquot of solution containing 100 g of Ni (II) in a separatory funnel, 10 ml of buffer solution of pH 7 and 12 ml 10^{-2}M HHMCP in chloroform were added. After shaking for 4 minutes, separatory funnel was kept for equilibrium and allowed to separate into two layers. The organic layer containing yellow coloured complex was collected in a 50 ml beaker containing a pinch of anhydrous sodium sulphate to remove traces of water. The absorbance of the extracted yellow complex was recorded at 495 nm against chloroform black. A calibration graph was prepared and unknown amount of Ni (II) was determined from the calibration curve. Raffinates were analyzed for determination of Ni (II).

Result and Discussion:

Spectral characteristics:

The absorbance spectra of the extracted complex in chloroform were compared with chloroform. It was found that the Ni (II) complex has λ_{max} at 495 nm

Effect of pH:

The absorbance of the organic phase was measured as a function of pH of the aqueous phase. The complexation of Ni (II) was carried out at pH range from 1-12. The data obtained shows (Table 1) maximum absorbance at pH 7. In more acidic or more basic solutions, it was found that absorbance decreases (Figure 1)

Table 1: Effect of pH on Ni (II) - HHMCP Complexation

1. Ni (II) = 100μg
2. HHMCP = 14 ml 10^{-2} M in Chloroform
3. Blank = Chloroform
4. Equilibrium period = 3 Minutes
5. λmax = 495 nm
6. pH = 01-12

pH	Absorbance
1.0	0.526
2.0	0.539
3.o	0.555
4.0	0.606
5.0	0.679
6.0	0.710
6.5	0.699
7.0	0.742
7.5	0.709
8.0	0.700
9.0	0.684
10.0	0.673
11.0	0.670
12.0	0.668

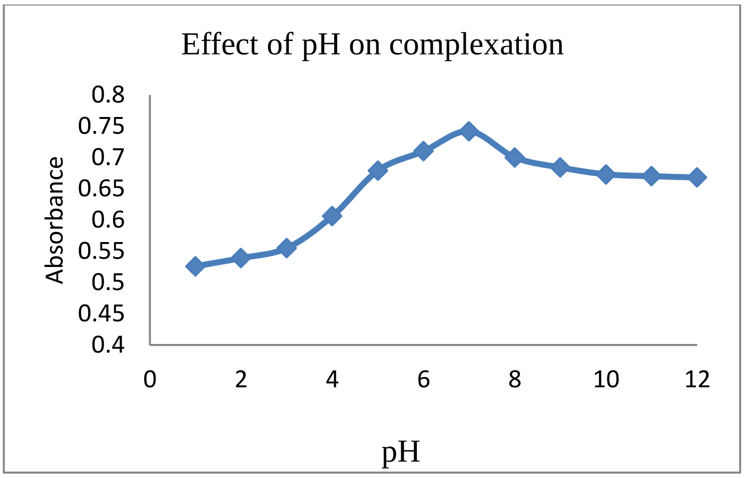

Fig. 1: Effect of pH on Ni(II)-HHMCP Complexation

Effect of reagent concentration:

The minimum amount of reagent required for complete complexation of 100µg of Ni (II) was studied by varying the concentration of HHMCP (Table 2). The results obtained from the plot of absorbance versus concentration of HHMCP indicate that 13 ml of 10^{-2}M reagent solution was sufficient for the quantitative extraction and spectrophotometric determination of 100µg Ni (II) (Figure 2). Addition of more reagent did not interfere with complexation and extraction of the complex. Further study of complexation was carried out by using 14 ml of 10^{-2} M HHMCP solution in chloroform to ensure the complete complexation.

Table 2: Effect of Reagent Concentration

Volume of 10^{-2} M HHMCP solution	Absorbance
3.0	0.588
4.0	0.590
5.0	0.599
6.0	0.614
7.0	0.623
8.0	0.633
9.0	0.652
10.0	0.670
11.0	0.689
12.0	0.710
13.0	0.738
14.0	0.738
15.0	0.738
16.0	0.738
18.0	0.738

1. Ni (II) = 100µg
2. HHMCP = 03-20 ml 10^{-2} M in Chloroform
3. Blank = Chloroform
4. Equilibrium period = 3 Minutes
5. λmax = 495 nm
6. pH = 7

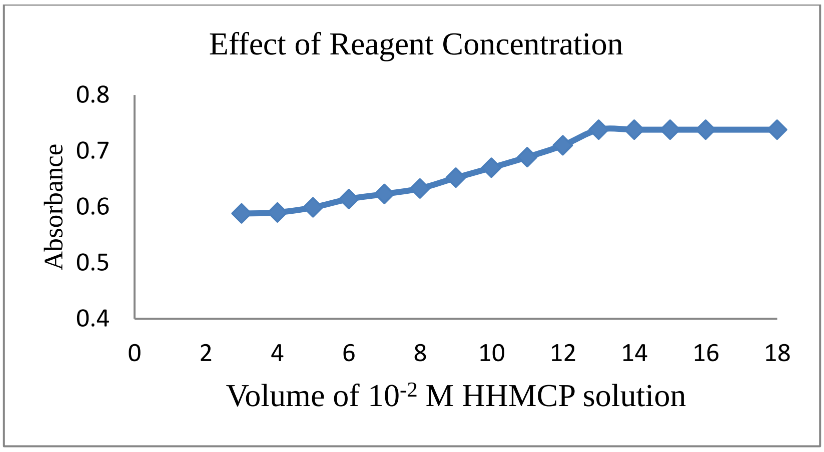

Fig. 2: Effect of HHMCP Concentration on extraction of Ni(II)

Effect of equilibrium time:

The minimum equilibrium time for complete complexation of 100µg Ni (II) was studied by varying the equilibrium period from 5 seconds to 10 minutes. (Table 3) The results obtained from the plot of absorbance versus equilibrium time indicated that minimum 1 minute equilibrium time was required for the quantitative extraction and spectrophotometric determination of 100µg of Ni (II) (Figure 3). It was also observed that equilibrium time above 1 minute did not affect the complexation and extraction of the complex. Thus further study of complexation was carried out by using 3 minutes as an equilibrium period.

Table 3: Effect of Equilibrium Time on Ni (II)- HHMCP Complexation

Equilibrium Time in Minutes	Absorbance
0.16	0.588
0.33	0.622
o.50	0.699
0.75	0.732
1.00	0.733
1.50	0.733
2.00	0.732
3.00	0.732
5.00	0.734
10.0	0.733

1. Ni (II) = 100µg
2. HHMCP = 14 ml 10^{-2} M in Chloroform
3. Blank = Chloroform
4. Equilibrium period = 10 Seconds – 10 Minutes
5. λmax = 495 nm
6. pH = 7

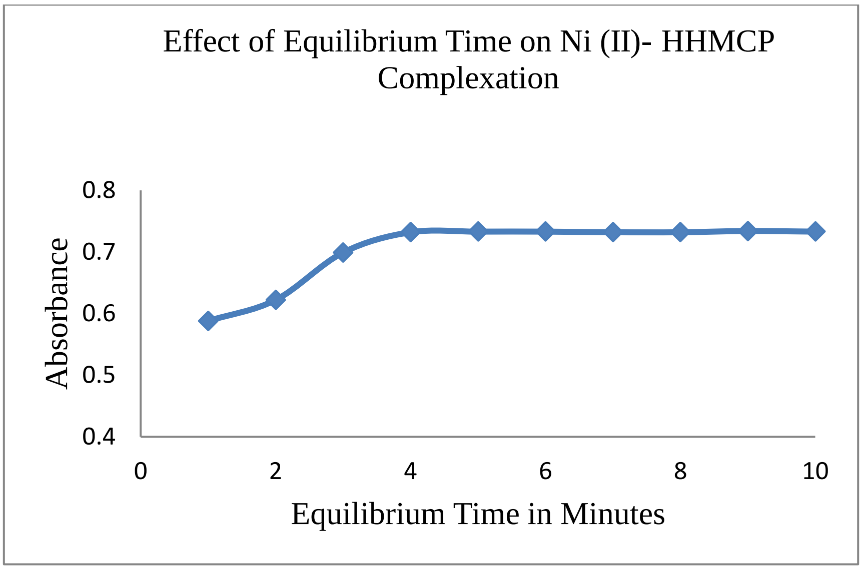

Fig. 3: Effect of Equilibrium Time on Ni (II)- HHMCP Complexation

Calibration curve and sandell's sensitivity:

A calibration graph of Ni (II) was prepared by complexing varying amount of Ni (II) in the range 0µg to 160µg with 14 ml 10^{-2}M HHMCP in chloroform (Table 4). Plot of absorbance versus concentration of Ni (II) gave a straight line indicating that that Beer's range up to 100µg of Ni (II) at 495 nm. (Figure 4)

Table 4: Calibration Curve for Ni (II)- HHMCP Complexation

Ni (II), ppm	Absorbance
0.0	0.0
20.0	0.094
40.0	0.210
60.0	0.388
80.0	0.567
100.0	0.737
120.0	0.830
140.0	0.915

1. Ni (II) = 20 – 140 ppm
2. HHMCP = 14 ml 10^{-2} M in Chloroform
3. Blank = Chloroform
4. Equilibrium Period = 03 Minutes
5. λmax = 495 nm
6. pH = 7

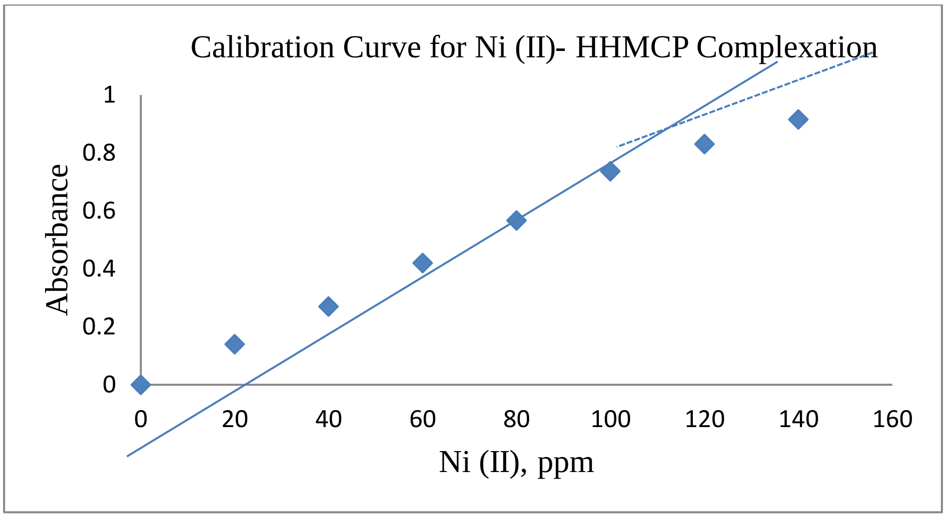

Fig. 4: Calibration Curve for Ni (II)- HHMCP Complexation

Mole ratio method:

Mole Ratio Method is used to determine the composition of the complex. Complexation was carried out by treating equimolar solutions of Ni (II) and HHMCP (Table 5). Plot of absorbance versus mole ratio gave two lines intercepting each other at mole fraction 1. This indicates metal to ligand ratio 1:1. (Figure 5)

Table 5: Mole Ratio Method:

Mole ratio	Absorbance
0.4	0.069
0.8	0.076
1.0	0.079
1.2	0.077
1.6	0.074
2.0	0.072

1. Ni (II) = 0.0017M
2. HHMCP = 0.0017 M in Chloroform
3. Blank = Chloroform
4. Equilibrium period = 03 Minutes
5. λmax = 495 nm
6. pH = 7

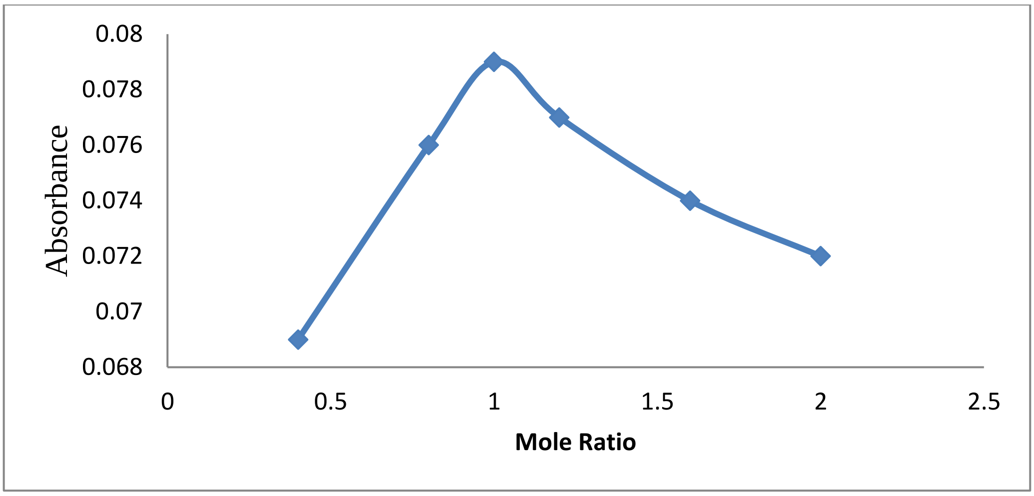

Fig. 5: Mole Ratio Method

Job's continuous variation method:

Job's Continuous Variation Method is also used to determine the composition of the complex. Complexation was carried out by treating equimolar solutions of Ni (II) and HHMCP (Table 6). For complexation of Ni (II) varying moles of Ni (II) were treated with varying moles of HHMCP in chloroform to obtain mole fraction 0.1 to 1.0. Plot of absorbance versus mole fraction also suggest metal to ligand ratio 1:1. (Figure 6)

Table 6: Job's Continuous Variation Method:

1. Ni (II) = 0.0017M
2. HHMCP = 0.0017 M in Chloroform
3. Blank = Chloroform
4. Equilibrium period = 03 Minutes
5. λmax = 495 nm
6. pH = 7

ml of Ni(II) (0.0017M)	ml of HHMCP (0.0017M)	ml of Chloroform	Mole Fraction	Absorbance
0.5	4.5	5.5	0.1	0.011
1.0	4.0	6.0	0.2	0.013
1.5	3.5	6.5	0.3	0.017
2.0	3.0	7.0	0.4	0.023
2.5	2.5	7.5	0.5	0.026
3.0	2.0	8.0	0.6	0.025
3.5	1.5	8.5	0.7	0.018
4.0	1.0	9.0	0.8	0.013
4.5	0.5	9.5	0.9	0.010

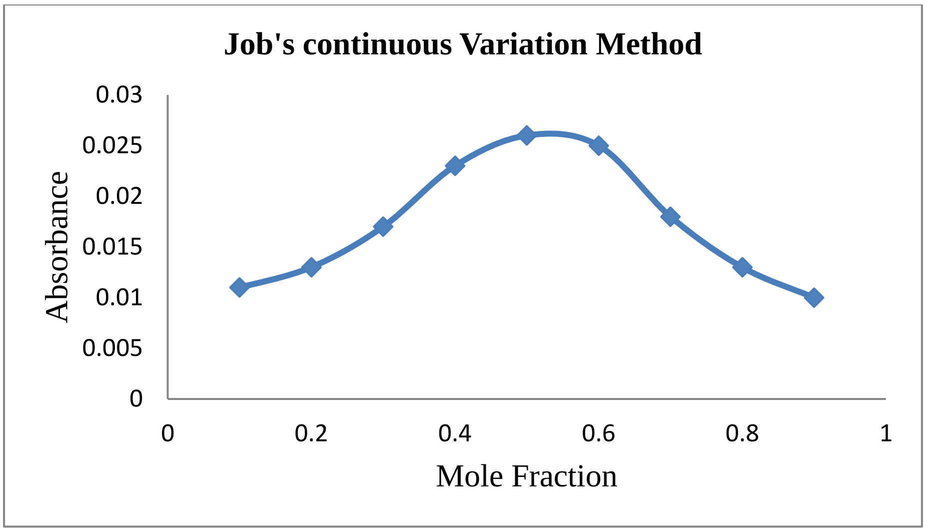

Fig. 6: Job's Continuous Variation Method

Effect of foreign ions:

Under the optimum conditions the effect of various cations and anions on the extraction and spectrophotometric determination of 100µg Ni (II) was studied by adding known amount of foreign ion in interest to Ni (II) aqueous solution before adjusting the required pH. Complexation was carried out as per the method mentioned above. (Table 7)

Table 7: Effect of Foreign Ions on Extraction of Ni (II)

1. Ni (II) = 100 µg/ml
2. HHMCP = 14 ml 10^{-2} M in Chloroform
3. Blank = Chloroform
4. Equilibrium period = 03 Minutes
5. λmax = 495 nm
6. pH = 7

Foreign Ion added	Amount Tolerated in µg
Sn (II)	20
Ru (II)	20
Mn (II)	10
Fe (II)	15
Co (II)	15
Cu (II)	15
Zn (II)	10
Cd (II)	10
Cr (VI)	30
Pd (II)	25

In case of intensive interference of some foreign ions the test was repeated with successively smaller amount of the same foreign ion. The tolerance for the added foreign ion was decided as the largest amount that give error less than 2 % in the extractive determination of Ni (II) at 495 nm $\lambda_{max.}$

Applications:

To study the analytical applicability of the proposed method, it was applied for separation and spectrophotometric determination of Ni (II) from real samples such as Ni (II) from Raney Nickel catalyst, monel metal etc. (Table 8). The results were compared with those obtained using the traditional methods. As seen, the results of two different methods are in satisfactory agreement.

Table 8: Determination of Ni (II) from real Samples

Samples	Ni (II) content (%)	
	Certified Value	From Complexation with HHMCP
Nickel Aluminum Alloy Powder	50	50
Monel Metal	67	66.4
Cupronickel	25	24.7

Conclusions:

An extractive spectrophotometric method was developed for estimation of Nickel (II). 2-[(E)-N-(2—{[2-[(E)-[(2-hydroxyphenyl) methylildene] amino] phenyl} (methyl) amino} phenyl) carboximidoyl] phenol (HHMCP) was synthesized[66] and successfully used for quantitative extraction of Nickel (II) at pH 7.0. Since the equilibration time is very less, the method is very quick. The method is applicable for determination of Nickel (II) from alloys and catalyst

References:

1. B. Patel, Nitin Kumar and K. K. Desai, *Asian J. Chem*., 15(2), 751-754 (2003).
2. K. Zarei, M. Atabati and Z. Malekshabani., *Anal. Chim. Acta*.556(1), 247-54 (2006).
3. A. P. Kumar, P. R. Reddy and V. K. Reddy, *J. Autom. Methods. Manag. Chem.*, 48768 (2007).
4. M. K. Naik and N. V. Thakkar, *Indian J. Chem*., 34A, 410-411 (1995).
5. G. A. Shar and G. A. Soomro, *The Nucleus*, 41(1-4), 77-82 (2004).
6. X. Fan, G. Zhang and C. Zhu, *Analyst*, 123, 109-112 (1998).
7. N. Hokoufi, F. Shemirani and F. Memarzeadeh, Anal. Chim. Acta., 601(2), 204-211 (2007).
8. Merian, E.; Anke, M.; Stoppler, M. *Elements and Their Compounds in the Environment*, Vol. 2, Wiley, VCH: Weinheim; 2004.
9. Wand, K. Nickel Trace Elements in Life Science, Chinese Measurement Press: Peking; 1991.
10. Zerner, B. *Bioorg. Chem.*1991, 19, 116.
11. Templeton, D. *Biological Monitoring of Chemical Exposure in the Workplace*, Word ealth Organization: Geneva; 1990.

12. Franson, M.A.H. *Standard Methods for Examination of Water and Waste Water*, American Publication Health Association; Washington, D.C., USA; 1995.
13. Lin, J.L. *J. Chin. Chem. Soc.*1986, 33, 215.
14. Yamamoto, Y.; Sugita, M.; Ueda K., *Bull. Chem. Soc. Jpn.* 1982, 55, 742.
15. Strelow, F.W.E.; Van der Walt, T.N., *Anal. Chim. Acta,* 1982, 136, 429.
16. Rydberg, J.; Musikas, C.; Choppin, G.R. *Principals and Practices of Solvent Extraction*, Marcel Dekker: New York; 1992.
17. Tuzen, M.; Melek, E.; Soylak, M. *J. Hazard. Mater.* 2006, 136, 597.
18. Rump, H.H.; Krist, H. Laboratory Manual for the Examination of Water, Waste Water and Soil, VCH Publisher: New York; 1988.
19. Onishi, H. Photometric Determination of Traces of Metals, Wiley-Interscience: New York; 1984.
20. Marczenko, Z. Separation and Spectrophotometric Determination of Elements, Ellis Harwood: New York; 1986.
21. W. J. Simmons**,** *Anal. Chem*., 45 (1973) 1947.
22. Chem. Eng. News, 54, No. 6 (1976) 6.
23. Chem. Eng. News, 54, No. 6 (1976) 7.
24. M. P. San Andres, M. L. Marina, and S. Vera, *Talanta*, 41, (1994) 179.
25. Thomas M, Ultraviolet and visible spectroscopy, in: Analytical Chemistry by Open learning, 2nd edition, Wiley, New York, 1996.
26. Prenesti E, Daniele PG, Toso S., *Anal Chim Acta*, 2002; 459: 323.
27. M Knochen, J Giglio., *Talanta,* 2004; 64: 1226.
28. N Teshima, N Fukui, T Sakai., *Talanta*, 2005; 68: 253.
29. Paleologos EK, Giokas DL, Karayannis MI., *Trends Anal Chem,* 2005; 24: 426.
30. Bosch Ojeda C, Sánchez Rojas F. Anal Bioanal Chem 2009; 394: 759.
31. Watanabe H, Saitoh T, Kamidate T, Haraguchi K, Mikrochim. Acta 1992; 106: 83.
32. Sombra L, Luconi M, Silva MF, Olsina RA, Fernandez LP., *Analyst,* 2001; 126: 1172.
33. Beiraghi A, Zarei AR, Babaee S., *Anal Sci,* 2007; 2: 527.
34. Beiraghi A, Babaee S., *Asian J Chem,* 2008; 20:1999.
35. Afkhami A, Madrakian T, Siampour H, J Braz Chem Soc 2006; 17: 797.
36. Manzoori LJ, Karim-Nezhad G., *Iran J Chem Chem Eng*, 2005: 2; 47.
37. Hassanien MM, Abdel-Rhman MH, El-Asmy AA., *Trans Metal Chem*, 2007; 32:1025.
38. Shemirani F, Jamali MR, Kozani RR., *Chem Analityczna*, 2007; 5: 327.
39. Silva MF, LP Fernandez, RA Olsina and D Stacchiola., *Anal Chim Acta*, 1997; 342:229.
40. MF Silva, Fernandez LP, Olsina RA., *Analyst,* 1998; 123:1803.

41. Garrido M, Di Nezio MS, Lista AG, Palomeque M, Fernández Band BS., *Anal Chim Acta*, 2004; 502: 173.
42. Afkhami A, Madrakian T, Siampour H., *Int J Environ Anal Chem*, 2006; 86: 1165.
43. Sohrabi MR, Farokhi E, Adnani A, Ziaian M., *J Appl Sci*, 2007; 7: 3123.
44. Madrakian T, Ghazizadeh F., *J Hazard Mater*, 2008; 153:695.
45. Shemirani F, Kozani RR, Jamali MR, Assadi Y, Hosseini MRM., *Int J Environ Anal Chem*, 2006; 86: 1105.
46. Laespada MEF, Pavon JLP, Cordero BM., *Analyst*, 1993; 118: 209.
47. Shemirani F, Kozani RR, Jamali MR, Assadi Y, Milani SMR., *Sep Sci Technol*,2005; 40: 2527.
48. Ferreira HS, Bezerra MDA, Costa Ferreira SL, *Microchim Acta*, 2006; 154: 163.
49. Madrakian T, Afkhami A, Mousavi A., *Talanta*, 2007; 71: 610.
50. Safavi A, Abdollahi H, Nezhad MRH, Kamali R., *Spectrochim Acta A*, 2004; 60: 2897.
51. Bezerra MA, Conceição ALB, Ferreira SLC., *Anal Bioanal Chem*, 2004; 378: 798.
52. Manzoori JL, Karim-Nezhad G., *Anal Chim Acta*, 2004; 521: 173.
53. Sun Z, Liang P, Ding Q, Cao J., *J Hazard Mater*, 2006; 137:943.
54. Shemirani F, Jamali MR, Kozani RR, Salavati-Niasari M., *Sep Sci Technol*, 2006; 41: 3065.
55. Afkhami A, Bahram M., *Microchim Acta*, 2006; 155: 403.
56. Shokoufi N, Shemirani F, Memarzadeh F., *Anal Chim Acta*, 2007; 601: 204.
57. Lemos VA, França RS, Moreira BO., *Sep Purif Technol*, 2007;54:349.
58. Lemos VA, Santos MS, David GT, Maciel MV, Bezerra MDA., *J Hazard Mater*, 2008; 159: 245.
59. Ghaedi M, Shokrollahi A, Ahmadi F, Rajabi HR, Soylak M., *J Hazard Mater*, 2008; 150: 533.
60. Amais RS, Tarley CRT., *Canadian J Anal Sci Spectrosc*, 2008; 53:130.
61. Escaleira LA, Saltelli RE, Oliveira EP, Carvalho MFB, Becerra MA., *Intern J Environ Anal Chem*, 2009; 89:515.
62. Ghaedi M, Shokrollahi A, Niknam K, Niknam E, Soylak M., *Cent Eur J Chem*, 2009; 7: 148.
63. Ghaedi M, Shokrollahi A, Niknam K, Soylak M., *Sep Sci Technol*, 2009; 44: 773.
64. Silva EL, Roldan PS, Giné MF., *J Hazard Mater*, 2009; 171:1133.
65. Sahin CA, Efecinar M, Satiroglu N., *J Hazard Mater*, 2010; 176:672.
66. Ghanasham B. Sathe, Vikas V. Vaidya, Ravindra G. Deshmukh, Maharudra B. Kekare, Vikas S. Kulkarni , Atul C. Chaskar, *Journal of Applicable Chemistry*, 2013, 2 (3): 433-437

ETHNOBOTANICAL EXPLORATION AND PHYTOCHEMICAL SCREENING OF *MORINGA OLEIFERA* LAM.: A CASE STUDY FROM BARGARH DISTRICT, ODISHA, INDIA

Elisa Padhan[1], Nihar Ranjan Nayak[2], Jijnasa Barik[3],
Ghanashyam Behera[4] and Alok Ranjan Sahu*[1]

[1]Department of Botany, Vikash Degree College, Barahaguda, Canal Chowk, Bargarh, Odisha
[2]Department of Botany, Guru Ghasidas Vishwavidyalaya (A Central Uni.) Bilaspur, (C. G.)
[3]Department of Botany, Government Degree College, Sundargarh, Odisha, India
[4]Department of Botany, Maa Manikeshwari University,
ManikyaVihar, Bhawanipatna, Odisha
*Corresponding author E-mail: alok.btgene@gmail.com

Abstract:

Moringa oleifera is the most widely cultivated pan-tropical species of a monogeneric family, the Moringaceae, which is native to the sub-Himalayan tracts of India, Pakistan, Bangladesh and Afghanistan. The plant parts of *Moringa* such as root, bark, leaf, flower, seed and gum are used variously to cure several diseases like diarrhoea, stomach disorder, carries of tooth, headache, appetizer, menorrhagia, stomach pain, filaria, ringworm, earache, gingivitis, pharyngitis, tonsillitis, cleaning of throat, conjunctivitis, kidney stone, diabetes, hicca, asthma, swelling of scrotum, piles, hiccup, blood purifier, etc. The results in this study for both aqueous and ethanolic extracts revealed the presence of the following phytochemical constituents saponins, flavonoids, terpenoids, cardiac glycosides and alkaloids (aqueous extract) and tannins, saponins, flavonoid, steroids, cardiac glycosides, anthroquinones and alkaloids (ethanolic extract) in moringa leaves. This is an indication that the *Moringa* leaves contained tannins, saponins, flavonoid, steroids, terpenoids, cardiac glycosides, anthroquinones and alkaloids as secondary metabolites.

Keywords: *Moringa oleifera*, Moringaceae, Ethnobotany, Phytochemical Screening, Bargarh District.

Introduction:

Moringa oleifera, also known as *Moringa pterygosperma* Gaertn, belong to the Moringaceae family of perennial angiosperm plants, which includes 12 other species (Olson, 2002). They are cultivated throughout tropical and subtropical areas of the world, where it is known by various vernacular names (Ramachandran *et al.*, 1980), with drumstick tree, horseradish tree, and malunggay being the most commonly found in the literature. *Moringa oleifera* is an edible plant. Studies have shown that its roots, bark, leaves, flowers, fruits and seeds contain a wide variety of nutritional and medicinal properties (Kumar *et al.*, 2010).

Phytochemical analyses have shown that its leaves are particularly rich in potassium, calcium, phosphorous, iron, vitamins A and D, essential amino acids, as well as such known antioxidants such as β-carotene, vitamin C, and flavonoids (Amaglo *et al.,* 2010). Antioxidants, antimicrobial, anticancer and anti-inflammatory are some of the biological activities exhibited by medicinal plants. Combinations of secondary metabolites which are bioactive compounds are the basis for biological activities of medicinal plants. Alkaloids, phenolic compounds, glycosides, anthraquinones and terpenoids are major classes of plant secondary metabolites. Exhibition of biological activities by plants through bioactive compounds present are based on parent plant relationship. Hence, the biological activities of medicinal plants signify the kind of bioactive compounds which are present in its extract. The application of medicinal plants in ethnomedicine depends on the information on the constituents of the secondary metabolites found in the plants. The ethnomedicinal plants have been the major sources of drugs and lead compounds for drug synthesis (Halilu *et al.,* 2013). The means of identifying new sources of therapeutically and industrially important bioactive compounds from plants is referred to as Phytochemical screening (Aman *et al.,* 2012). Botanical identification, extraction with suitable solvents, purification and characterization of the bioactive constituents of medicinal plants are the processes involved in phytochemical screening (Bandaranayake, 2006). Most applications of bioactive compounds in pharmaceuticals, food preservation, alternative and natural therapies are based on antimicrobial activity (Kemal *et al.,* 2013). As a result, increased prevalence of microbial antibiotic resistance to the most common antibiotics (antimicrobial agents), evaluation of the antimicrobial activity of natural products has become so critical.

Sahu *et al.,* (2010) reported that the leaf juice and seeds of *Moringa oleifera* Lam. were used to regulate blood pressure, weakness, and diabetes by the native of Bargarh district, Odisha, India. Sahu *et al.,* (2013) reported that the leaf juice, and bark powder of *M. oleifera* Lam. used to regulate blood pressure, weakness, and rheumatism, respectively by the native of Sohela block of Bargarh district. Sahu and Sahu (2019) reported that leaves of *M. oleifera* Lam. are eaten after frying or roasting., fruits are eaten after frying or curry preparation; leaves juice and seeds were also used for the treatment of blood Pressure, anti-diabetic, hepatoprotective, anti-inflammatory, anticancer, antimicrobial, antioxidant, cardiovascular, antiulcer, antiallergic, wound healing by the native of Bargarh district. Sahu and Ekka (2021) reported that the leaves of *M. oleifera* Lam. are cooked dried and also with mung dal and vegetables used as curry by the native of Bargarh district, Western Odisha, India. Mishra *et al.,* (2022) reported that equal amount of the bark of *M. oleifera* Lam.*, Ficus glomerata Roxb.* and *Syzygium cumini* (L.) Skeels are crushed together and applied externally to cure blisters by the Native of Bargarh District, Odisha, India. Sahu and Sahu (2022) reported that the leaves and fruits of *M. oleifera* Lam are used as leafy vegetables and vegetables by the tribal peoples of Jharigaon Block of Nabarangpur district, Odisha, India. Dash and Sahu (2023) reported that leaves, seeds, bark, roots, sap and flowers were used as food by cooking and have some medicinal values like antiasthmatic, anti-diabetic, hepatoprotective, anti-inflammatory, anticancer, antimicrobial, antioxidant, antiulcer, cardiovascular properties.

People of Bargarh district use the plants for various purposes, but till yet no document available on phytochemical screening of this essential plant from the study site. Keeping these in mind the present study deals with the study of documenting the medicinal use and phytochemical screening of the *Moringa oleifera* Lam.

Materials and Methods:

Study area

Bargarh district lies in the western part of Odisha, bordering Chhattisgarh. It is located at an altitude of 171 meters above sea level with a latitude and longitude of 21.342585° North and 83.624199° East, respectively. It consists of 12 blocks under two subdivisions namely Bargarh and Padampur. The climate of the Bargarh district is mostly tropical and temperate. The average temperature during summer season is about 46º C and during winter, it is roughly around 10º C. The land area of Bargarh district is about 5837 square kilometers, of which, about 1216.13 square kilometers (20.83%) is covered in forest area. The population of Bargarh district is around 1.481 million according to the 2011 census.

Ethnomedicinal observations

An ethnobotanical survey was conducted in different forest localities and villages of Bargarh district during 2024-25. A number of plant species were collected and preserved. The people of different races (such as herbal medicine practitioners, Kabirajs, Vaidyas, village head experience old men and women) were contacted, discussed and interviewed about the ethnomedicinal value of the collected specimens. Out of a number of plant species collected *Moringa* is found to be an interesting cultivated plant which is not only nutritionally important but also medicinally very much precious (Figure 1). In order to establish the authenticity of ethnomedicinal uses, the collected data has been cross checked with some scientific literatures (Sahu *et al.,* 2010; Sahu *et al.,* 2013, Sahu and Sahu, 2017, 2020).

Sampling and collection of leaves

The experiment was conducted in the year 2024 -25 in the college laboratory. Leaves were collected from the *Moringa oleifera* plant from the garden. It ensured that the plant was healthy and uninfected. The leaves were washed under running tap water to eliminate dust and other foreign particles and to cleanse the leaves thoroughly and dried.

i. Aqueous extract: This was carried out through the use of pestle and mortar, dry powder of *Moringa* leaves was homogenized at a ratio of 1:8 w/v in sterile distilled water and filtered through muslin cloth. This was followed by strained of filtrate obtained through filter paper (Whattman No. 1). The extraction procedure was done at room temperature.

ii. Ethanolic extract: This was prepared by soaking 400g of the dry *Moringa* leaves in 1000ml of ethanol for 48hrs at room temperature. Thereafter, extract was filtered through a Whatmann filter paper No. 42 (125mm) and subsequently through cotton wool. The extract was then concentrated using a rotary evaporator with the water bath set at 40°C was used to concentrate extract to one-tenth its original volume and finally with a freeze drier. This was followed by storage of dried residue at 4ºC. The crude extract residue was then weighed and dissolved in distilled water for experimental analysis.

Phytochemical screening

Tests were carried out on the aqueous extract to identify the phyto constituents using standard procedures as described by (Rani *et al.,* 2025; Sahu *et al.,* 2024; Sharma *et al.,* 2024; Nayak *et al.,* 2024).

Test for Tannins: This was done by boiling 1g of each of the dried powdered samples (separately) in 40 ml of water in a test tube and then filtered. A brownish green or a blue-black coloration was observed after addition of a few drops of 0.1% ferric chloride.

Test for Phlobatannins: An aqueous extract of the dry *Moringa* leaves was boiled with 1% aqueous hydrochloric acid. Appearance of red precipitate indicates the presence of phlobatannins.

Test for Saponins: To 10 ml of distilled water, 1 g of the powdered dry *Moringa* leaves (separately) was added and boiled in a water bath. The mixture was then filtered and to resultant 5ml of filtrate, 2-3 ml of distilled water was added and shook vigorously for attainment of a stable persistent froth. Then, followed by a mixture of frothing with 1-2 drops of olive oil and shook vigorously, then observed in the formation of emulsions.

Test for Flavonoids: This was determined through heating 0.5g of the dry powdered of *Moringa* leaves extract sample (separately) with ethyl acetate (10 ml) over a steam water bath for 3 min. To 1 ml of dilute ammonia solution, 4ml of filtrate from the filtered mixture mixture was added and shook. Appearance of yellow coloration is an indication of presence of flavonoids.

Test for Steroids: This was carried out by addition of 4 ml of acetic anhydride to 1 g of each of the crude extract (separately) with further addition of H_2SO_4(2ml). The presence of steroids was indicated by a change of colour from violet to blue or green.

Test for Terpenoids: This was carried out by Salkowski‟s test described by Parekh and Chands (2008), To 4ml of chloroform, 10ml of the crude extract was added, followed by the careful further addition of 5ml concentrated (H_2SO_4). Formation of the reddish-brown coloration at the interface is an indication of a positive result for the presence of terpenoids.

Test for Cardiac Glycosides: The Keller-Killani test method described by Parekh and Chands (2008) was used for Cardiac Glycosides determination. To 2 ml of glacial acetic acid containing one drop of ferric chloride ($FeCl_3$) solution, 5 ml of the plant extract was added, this was followed by addition of 1 ml concentrated Sulfuric acid. Brown ring was formed at the interface which indicated the presence of deoxy sugar of cardenolides. A violet ring may appear below the brown ring, though in the acetic acid layer, a greenish ring may also form just progressively throughout the layer.

Test for Anthroquinones: 5 ml of each of the plant extracts was boiled with 10 ml of sulfuric acid (H_2SO_4) and was filtered while hot. The filtrate was shaken with 5 ml of chloroform. The chloroform layer was pipette into another test tube and 1 ml of dilute ammonia was added. The resulting solution was observed for color changes (Sofowara, 1993).

Test for Alkaloids: 5 ml of the *Moringa* leaves extracts were added to 8 ml of 1% HCl mixed, warmed and later filtered. Maeyer's and Dragendorff's reagents were added to the 2 ml of the filtrate, then alkaloids' absence or presences were determined based on the turbidity or precipitate development (Parekh and Chands, 2008).

Results:

Ethnomedicinal observations

As recorded Drumstick tree is a multi-utility and multifarious drug plant. All parts of the plant are used as medicines. The present paper highlights the ethnomedicinal uses of different parts of this valuable plan by the native of Bargarh district (Table 1).

Phytochemical screening

The results in this study for both aqueous and ethanolic extracts revealed the presence of the following phytochemical constituents saponins, flavonoids, terpenoids, cardiac glycosides and alkaloids (aqueous extract) and tannins, saponins, flavonoid, steroids, cardiac glycosides, anthroquinones and alkaloids (ethanolic extract) in *Moringa* leaves (Table 2). This is an indication that the *Moringa* leaves contained tannins, saponins, flavonoid, steroids, terpenoids, cardiac glycosides, anthroquinones and alkaloids as secondary metabolites.

Discussion:

The plant parts of *Moringa* such as root, bark, leaf, flower, seed and gum are used variously to cure several diseases like diarrhoea, stomach disorder, carries of tooth, headache, appetizer, menorrhagia, stomach pain, filaria, ringworm, earache, gingivitis, pharyngitis, tonsillitis, cleaning of throat, conjunctivitis, kidney stone, diabetes, hicca, asthma, swelling of scrotum, piles, hiccup, Infantile constipation, cut wound, blood purifier, smooth delivery, galactogogue, black spot, jaundice, tuberculosis, infant's eye problem, eye pain, constipation, Oedema, eczema, acne, blister, erysipelas, boil, whitlow, arthritis, spleen enlargement, kidney problem, hydrocoel, anthelmintic, premature ejaculation, tooth gum pain, throat pain, waist pain, eye swelling, redness of eye, aphrodisiac, urinary tract inflammation, senselessness, rheumatoid arthritis, gout, joint pain, eye inflammation, earache, leprotic wound and night blindness. Sahu *et al.*, (2010) reported that the leaf juice and seeds of *Moringa oleifera* Lam. were used to regulate blood pressure, weakness, and diabetes by the native of Bargarh district, Odisha, India. Sahu *et al.*, (2013) reported that the leaf juice, and bark powder of *M. oleifera* Lam. used to regulate blood pressure, weakness, and rheumatism, respectively by the native of Sohela block of Bargarh district. Sahu and Sahu (2019) reported that leaves of *M. oleifera* Lam. are eaten after frying or roasting., fruits are eaten after frying or curry preparation; leaves juice and seeds were also used for the treatment of blood Pressure, anti-diabetic, hepatoprotective, anti-inflammatory, anticancer, antimicrobial, antioxidant, cardiovascular, antiulcer, antiallergic, wound healing by the native of Bargarh district. Sahu and Ekka (2021) reported that the leaves of *M. oleifera* Lam. are cooked dried and also with mung dal and vegetables used as curry by the native of Bargarh district, Western Odisha, India. Mishra *et al.,* (2022) reported that equal amounts of the bark of *M. oleifera* Lam.*, Ficus glomerata Roxb.* and *Syzygium cumini* (L.) Skeels are crushed together and applied externally to cure blisters by the Native of Bargarh District, Odisha, India. Sahu and Sahu (2022) reported that the leaves and fruits of *M. oleifera* Lam are used as leafy vegetables and vegetables by the tribal peoples of Jharigaon Block of Nabarangpur district, Odisha, India. Dash and Sahu (2023) reported that leaves, seeds, bark, roots, sap and flowers were used as food by cooking and have some medicinal values like antiasthmatic, anti-diabetic, hepatoprotective, anti-inflammatory, anticancer, antimicrobial, antioxidant, antiulcer, cardiovascular properties.

The results in this study for both aqueous and ethanolic extracts revealed the presence of the following phytochemical constituents saponins, flavonoids, terpenoids, cardiac glycosides and alkaloids (aqueous extract) and tannins, saponins, flavonoid, steroids, cardiac glycosides, anthroquinones and alkaloids (ethanolic extract) in moringa leaves. This is an indication that the Moringa leaves contained tannins, saponins, flavonoid, steroids, terpenoids, cardiac glycosides, anthroquinones and alkaloids as secondary metabolites. Several functions and roles are attributed to flavonoids in humans and animals; this includes protection and fight against inflammatory disorders, allergies, diarrhea, microbes‟ invasion, platelet aggregation, ulcers, hepatotoxins, viruses, and tumors (Kumar *et al.,* 2010). Flavonoids were able to achieved the aforementioned properties because of their antipyretic (fever-reducing), antioxidant, analgesic (pain-relieving), and spasmolytic (spasm-inhibiting) activities (Krishnaiah *et al.,* 2009). The presence of epicatechin, quercetin and luteolin in flavonoids plays pivotal roles in inhibition of fluids that are responsible for diarrhea (Krishnaiah *et al.,* 2009).

Acknowledgment:

The author (ARS) is thankful and obliged to the Principal of Vikash Degree College, and Chairman of Lashmi's Vikash Group of Institutions for providing us with the entire necessary infrastructure for the study.

References:

1. Amaglo NK, Bennett RN, Lo Curto RB, Rosa EAS, Lo Turco V, Giuffrid A, Lo Curto A, Crea F and Timpo GM (2010): Profiling selected phytochemicals and nutrients in different tissues of the multipurpose tree *Moringa oleifera* L., grown in Ghana. Food Chem. 122, 1047–105410.1016/j.
2. Aman, D., Getahun, T. and Reneela P (2012): Isolation and characterization of natural

products from *Helinus mystachnus* (Rhamnaceae). Journal of Chemical and Pharmaceutical Research, 4 (3): 1756-1762.

3. Dash S and Sahu AR (2023): A preliminary report on the use of leafy vegetables by the native of Balangir district, Western Odisha, India. In Research Trends in Plant Sience, Bangar M, Bai BP, Dasgupta S and Yadav S (eds.). Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, INDIA. Chr. 11, Pp. 83-97. **(**ISBN: 978-93-88901-68-0).
4. Halilu ME, October N, Balogun M, Musa KY, and Abubakar MS (2013): Isolation and characterization of triterpenesfrom petroleum ether ethyl acetate extracts of stem bark of Parinaricurtellifolia Planch Ex. Benth (Chrysobalanaceae).Chemistry and Material Reseach, 3 (9): 100-104.
5. Kemal D, Elvira K, Haris N and Emin S (2013): Antibacterial Activity ofMethanolic Extracts, Decoction and Isolatedtriterpene products from different parts of Birch, *Betula pendula*, Roth. Journal of Plant Studies, 2 (2): 61-70.
6. Krishnaiah D, Devi T, Bono A and Sarbatly R (2009): Studies on phytochemical constituents of six Malaysian medicinal plants. Journal of Medicinal Plants Research, 3 (2): 067-072.
7. Kumar PS, Mishra D, Ghosh G and Panda GS (2010): Medicinal uses and pharmacological properties of *Moringa oleifera*. Int. J. Phytomed. 2: 210–216.
8. Mishra S, Sahu M, and Sahu AR (2022): Medicinal plants used for the treatment of various skin disorders by the native of Bargarh district, Odisha, India. In Recent Trends and Advances in Medicinal Plants Research, Soni PK (eds.) PK Publishers and Distributors, 4th Pustak Kartar Nagar, New Delhi, Chapter 11, Pp. 121-130. (ISBN: 978-81-953735-8-1).
9. Nayak NR, Pattnayak A and Sahu AR (2024): Screening for Phytochemicals, antimicrobial and anticoagulant activity of aqueous extract of *Tridax procumbence.* In Research and Reviews in Plant Sciences Volume II; Srivastava MP, Bangar MA, Chachad D, and Kumar AR (Ed.). Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, INDIA. Pp. 115-126.
10. Parekh M, and Chanda K (2007): *In-vitro* antibacterial activity of crude methanol extracts of *Woodfordia fruticosa* Kurz flower (Lythaceae). Brazillian Journals of Microbiology, 38: 2
11. Ramachandran C, Peter KV, and Gopalakrishnan PK (1980): Drumstick (*Moringa oleifera*): a multipurpose Indian vegetable. Econ. Bot., 34: 276–283.
12. Rani JJ, Tripathi G, Pattanayak S, Boxi S, Rout S, Kumar S and Sahu AR (2025): Phytochemical and cytotoxic analysis of bulbs of *Drimia indica* (Jungli piyaz): a medicinal plant of Asparagaceae. In Plants and Secondary Metabolites, Hossain E, Roy BC, Jena N and Kumar S (Eds.), Volume 4, Chr. 6, P.p. 52-61. DOI: https://doi.org/10.5281/zenodo.14845056.

13. Sahu AR and Sahu M (2019): A preliminary report on home garden for nutritional and primary health security of rural people of Bargarh District in Western Odisha, India. World Journal of Pharmacy and Pharmaceutical Sciences, 8(7):1383-1394. (DOI: 10.20959/wjpps20197-14174).
14. Sahu AR and Sahu M (2020): A preliminary report on the ethnobotanical plants used for dental care by the tribal of Bargarh District, Western Odisha. World Journal of Pharmacy and Pharmaceutical Sciences, 9 (2):1020-1028. (DOI: 10.20959/wjpps20202-15463).
15. Sahu AR and Sahu M (2022): Green leafy vegetables used by the Tribal Peoples of Jharigaon Block of Nabarangpur District, Odisha, India. In Ecology Research, Jachak *et al.*, Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, INDIA. Volume V, Chapter 7:52-59.
16. Sahu AR, and Ekka NJ (2021): A preliminary report on the use of leafy vegetables by the native of Bargarh district, Western Odisha, India. International Journal of Applied Research, 7(5): 218-223 (DOI: https://doi.org/10.22271/allresearch.2021.v7.i5d.8567).
17. Sahu AR, Behera N and Mishra SP (2010): Use of Ethnomedicinal Plants by Natives of Bargarh District of Orissa, India. Ethnobotanical Leaflets, 14: 889-910.
18. Sahu AR, Nayak AK and Panigrahi SK (2013): Survey of some important ethno-medicinal plants of Sohela Block, Western Odisha, India. Life Sciences Leaflets, 11(11): 1-9.
19. Sahu AR, Nayak NR, and Ekka NJ (2024): A mini-review on phytochemical screening, biological activity, and therapeutic capability of *Hibiscus*: An ornamental plant species. In Research and Reviews in Plant Sciences; Chachad D, Mishra S, Mahishi P, and Sahu AR (Ed.). Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, INDIA. Volume IV, Pp. 72-80.
20. Sahu M and Sahu AR (2017): A Preliminary Report on the Traditional Practice for Dental and Oral Health Care in Bargarh District of Western Odisha, India. Journal of Medicinal Plants Studies, 5(5):120-125.
21. Sharma A, Lal S, Sharma BP, Rathore S, Sahu AR, Jena N and Kumar S (2024): Phytochemical analysis of *Marsilea minuta* L.: an aquatic medicinal plant. In Medico Bio-wealth of India, Vimala K, Choudhary JR and Das SK(Eds.), APRF Publishers, India. Vol. 15, Chr. 2, P.p. 11-20. DOI: https://doi.org/10.5281/zenodo.11123606.
22. Sofowora A (1993): A. *Medicinal Plants and Traditional Medicine in Africa.* Spectrum Books Ltd., Ibadan, Nigeria, pp, 191-289.

Table 1: Ethnomedicinal use of various parts of *Moringa oleifera* Lam. by the native of Bargarh district, Odisha, India

Plant parts	Disease	Dosage form
Root	Filaria	Root paste is warmed and applied over the affected part.
	Ringworm	Root (white variety plant) paste is applied over the affected part.
	Earache	Root extract of the plant, honey, *Sesamum indicum* seed oil and rock salt are mixed together and used as ear drops (3 drops) 3-4 times daily.
	Diabetes	Root decoction (4 teaspoon) is taken 3 times daily regularly.
Leaf	Diarrhoea and Stomach disorder	Leaf extract (1 teaspoon) is taken along with honey (1 teaspoon) and a glass of coconut water 2-3 times daily.
	Asthma	Leaf (10 gm) is boiled in water (200ml) for 5 minutes and filtered. The decoction is mixed with a pinch of salt, fruit powder of *Piper nigrum* (10 numbers) and fruit juice of *Citrus lemon* (2-3 teaspoon) and is taken once daily in empty stomach.
	Blood purifier	Leaf extract is used as tonic and given to the children as blood purifier and to strengthen their bones.
	Jaundice	Leaf extract (1 teaspoon) is taken along with honey (1 teaspoon) and coconut water (250 ml) 3 times daily for 15 days.
Bark	Headache	Bark extract mixed with jaggery is sniffed.
	Gingivitis	Bark paste is applied on the affected gum.
	Ringworm	Bark crushed with radish (*Raphanus raphanistrum*) and is applied over the affected part.
	Hydrocoel	Equal amount of bark powder and seed powder of mustard crushed together and the paste is applied over the affected part.
Flower	Eye swelling and redness of eye	Fresh flowers are crushed to paste and warmed. It is applied over the eyries.
	Urinary tract inflammation	Fresh flower extract (1 teaspoon) is taken along with coconut water (half a glass) 2 times daily.
Seed	Earache	Seed extract (2-3 drops) is poured in to the ear.
	Menorrhagia	Seed powder (1-3 g) is taken 2 times daily.
	Stomach pain	Seed powder (1-3 g) is taken 2 times daily to cure stomach pain during menstrual cycle.
Gum	Headache	Gum is crushed with cow milk and is applied on forehead.
	Boil	Gum is rubbed on a stone with cow milk and is applied over the affected part.

Table 2: Preliminary phytochemical screening from the leaves of *Moringa oleifera*

Plant Constituent	Extracts	
	Aqueous Extract	Ethanol Extract
Tannins	-	++
Phlobatannins	--	--
Saponins	++	+++
Flavonoids	++	+++
Steroids	-	+++
Terpenoids	+	-
Cardiac Glycosides	+	+
Anthroquinones	-	+
Alkaloids	+	+++

Legend: +++ = very much, ++ = much, + = little, – = nil

Fig. 1: Photograph of entire *plant (a), barks (b), flowers (c), leaves (d), fruits (d) and seeds (f) of Moringa oleifera* Lam.

ROLE OF TECHNOLOGY IN PROVIDING INCLUSIVE EDUCATION IN RURAL INDIA: A SURVEY OF RURAL VILLAGES IN INDIA

Abhavya Sharma, Tsering Palmo, Vanshika Singh, Anshuman Negi and Raheel Hassan

Department of Computer Science and Applications,

Sharda University Greater Noida, Uttar Pradesh, India

Abstract:

This chapter examines how important technology is to advancing inclusive education in rural India. Even if digital innovations have made learning settings better in urban areas, rural areas still face significant challenges such poor infrastructure, a lack of digital literacy, issues with affordability, and cultural opposition. The chapter explores how judicious use of technology could bridge these gaps by facilitating individualized learning, expanding access to educational materials, and empowering educators. Drawing from real-world experiences and community viewpoints, it highlights the intricacies of digital exclusion and the significance of locally specific, context-sensitive strategies. The suggested projects place a high priority on curriculum innovation, community involvement, infrastructure development, and capacity growth.

Keywords: Sustainable Development Goal, Teacher Training, E-Learning Access, Digital Literacy, Inclusive Education, Rural India

Introduction:

Not only is education a fundamental human right, but it is also the foundation upon which societies shape progress and individuals build their futures. In the global endeavor to accomplish the Sustainable Development Goals (SDGs) of the United Nations, Goal 4—ensuring inclusive and equitable quality education and encouraging lifelong learning opportunities for all—is a fundamental principle. Recent decades have seen a revolution in education thanks to technology, which has made classrooms more inclusive, approachable, and engaging. Even as metropolitan areas gain from digital breakthroughs, rural India continues to face significant challenges that widen the educational divide.

Collaboration, vision, and context-specific interventions are necessary to bridge this difference in addition to infrastructure. The rapid pace of digital development is both an opportunity and a challenge. If technology is not employed effectively, it can exacerbate the gaps that currently exist. Digital education must therefore be viewed as a tool, not an end in itself, for building an inclusive, equitable, and progressive educational ecosystem.

This chapter examines the ways in which inclusive education in rural India can be successfully supported by technology. It highlights how digital tools may change lives, the pressing problems that keep them from being widely used in rural regions, and the community voices that lend authenticity to these realities. Through strategic insights and practical recommendations, this chapter aims to chart a path for educational justice in the digital era. not merely a fundamental right, but the foundation upon which individuals build their futures and communities shape their progress. In the global endeavor to accomplish the Sustainable Development Goals (SDGs) of the United Nations, Goal 4—ensuring inclusive and equitable quality education and encouraging lifelong learning opportunities for all—is a fundamental principle. Recent decades have seen a revolution in education thanks to technology, which has made classrooms more inclusive, approachable, and engaging. Even as metropolitan areas gain from digital breakthroughs, rural India continues to face significant challenges that widen the educational divide.

This chapter examines the ways in which inclusive education in rural India can be successfully supported by technology. It highlights how digital tools may change lives, the pressing problems that keep them from being widely used in rural regions, and the community voices that lend authenticity to these realities. Through strategic insights and practical recommendations, this chapter aims to chart a path for educational justice in the digital era.

Survey Locations and Methodology

Located in Panchayatan Inayatpur, the villages of Milak Lachchhi and Chirasi were selected for this study because to their diverse population and significant educational obstacles. These towns face challenges like inadequate internet, a lack of computers, and a lack of knowledge about how to use technology for education. These issues are a part of a much bigger tale that is occurring throughout rural India and are not simply exclusive to these two villages. Because they lack the tools or assistance necessary to make it work, many institutions like this one lose out on the benefits that technology can offer to education. By concentrating on Milak Lachchhi and Chirasi, we sought to comprehend the actual difficulties that families, educators, and kids deal with on a daily basis.

Survey design

We employed a variety of techniques to ensure that we got the whole picture. Through the use of structured surveys, we were able to collect important data regarding people's financial circumstances, access to technology, level of comfort with it, and opinions toward its use in education. We also had group talks and one-on-one interviews with important village residents and community members to learn more about their actual experiences. Through these discussions, we were better able to comprehend their difficulties and potential solutions.

Sample population

We employed a sample strategy that includes individuals from a range of age, gender, and economic brackets to ensure that everyone's perspective was heard. We were able to gain a comprehensive and well-rounded understanding of the opinions and experiences of people from many walks of life thanks to this method.

Data collection

In each village, our survey teams visited a thousand to fifteen hundred residences and spoke with families. The availability of gadgets like computers and smartphones, internet connectivity, and how individuals use these resources for education were among the topics they posed. Also, teams noted the availability of technology tools in households and schools and the ease of use by teachers and pupils. We were able to see the gaps more clearly by paying attention to these nuances.

Analysis framework

We concentrated on figuring out what is lacking, such as internet access, device access, or basic tech skills, and how the existing systems are functioning (or not). We contrasted our findings with other international education targets, such as the Sustainable Development Goal 4 of the UN, which aims to provide all people with high-quality education. This gave us a better understanding of how technology is contributing to inclusive education and where more work needs to be done.

Visit 1: Milak Lachchhi Village

Milak Lachchhi, a tiny village with 1,500 residents close to Greater Noida, Uttar Pradesh, was the destination of our first visit. The majority of families rely on farming as their source of income. Nonetheless, the hamlet has significant obstacles in the area of education. The majority of families lack smartphones, computers, or tablets that kids could use for learning, and the schools in this area lack basic digital resources. Additionally, students have very limited access to the internet, which makes it challenging for them to access online materials and communicate with the outside world. During house visits and group talks with 100 families, we discovered that the majority of parents were unaware of the ways in which technology may support their kids' education. The community shown a great deal of hope in spite of these challenges. If given access to reasonably priced technology and the right instruction, many educators and parents stated that they would gladly embrace it. Even setting up communal areas for learning and exploration, such as a community tech center, was something they recommended. This visit demonstrated to us the enormous potential for enhancing education in Milak Lachchhi through the introduction of easily navigable technologies. For digital learning to be a reality in the village, a comprehensive strategy that includes community engagement and teacher training is required, not simply gadgets and internet.

Visit 2: Chirasi, Panchayatan Inayatpur Village

Our second stop was Chirasi, a bigger village with roughly 1,800 inhabitants in Panchayatan Inayatpur. Chirasi encounters significant obstacles with regard to educational technology, just like Milak Lachchhi. Most homes do not have internet connectivity, and schools lack computers and even the most basic tools for digital instruction. Despite the fact that many households own cellphones, children rarely have the opportunity to utilize them for academic purposes because they are frequently shared by multiple people. We heard a lot of frustration when we spoke with children, parents, and instructors. Parents are concerned about their kids slipping behind, particularly because a lot of professions nowadays need digital abilities. Teachers expressed a desire to assist children in learning using technology, yet many feel excluded due to a lack of support and training. The people' readiness to accept change, however, was noteworthy. If they had guidance and access to reasonably priced solutions, they were ready to learn and apply technology. This trip demonstrated that Chirasi need answers tailored to the village's unique requirements, not merely gadgets. This can entail creating a common online learning environment, granting internet connection to strategic locations, and conducting training sessions to teach educators and learners how to use technology efficiently.

Contrasting insights:

When we compared Milak Lachchhi and Chirasi Panchayatan Inayatpur, we found that although both villages face similar difficulties in gaining access to technology for education, their responses to these difficulties varies greatly. The main challenges in both locations are low levels of digital literacy, restricted access to gadgets, and unreliable internet. Financial limitations are especially severe for Milak Lachchhi, making it even more difficult for families to purchase the required technologies. The majority of households depend on rudimentary infrastructure, and the technological divide in education is evident. Chirasi has somewhat more resources accessible, but not nearly enough to match the demand, even though access restrictions are still same. Nonetheless, there are also notable distinctions between these towns' perspectives and methods for handling the issue. Many people in Milak Lachchhi voiced doubts about the benefits of online learning. They weren't sure if it would actually help their kids in such a rural area where basic necessities like water and sanitary facilities still come first. Hesitancy existed because they had not seen concrete examples of how technology could benefit them. The people of Chirasi, however, were more receptive. They wanted to attempt and were interested, particularly if there was outside assistance like equipment donations or training. A increasing desire for change was indicated by this openness, which was positive. The lack of reasonably priced, useful technology and teacher training were problems that both villages confronted in spite of these distinctions. However, the way these challenges were addressed differed.

If the proper resources were available, Chirasi was prepared to act, but Milak Lachchhi need more time and assistance to help the community comprehend the advantages of digital education. There isn't a single solution that will work everywhere, as these divergent observations demonstrate. It is evident that a customized strategy is required, one that takes into account the local environment, the particular requirements of every village, and the community's views about technology.

Discussion:

We got the opportunity to sit down with the locals, hear their tales, and comprehend the actual educational obstacles they confront when we visited Milak Lachchhi and Chirasi, Panchayatan Inayatpur. It became evident that one major problem is access to technology. The internet is hardly available in classrooms, teachers lack the necessary expertise to use technology efficiently, and schools lack the resources to make classes more interesting. What most impressed me, in spite of all these obstacles, was how receptive and eager the community is to adopt technology if given the opportunity. If we can meet them halfway and offer the appropriate kind of support, there is a lot of opportunity here.

1. How technology affects learning

Imagine the impact education could have in these villages if students were equipped with the appropriate resources. Imagine if every child had access to a tablet so they could view instructional videos, engage with their lessons, or even take online courses. The options are limitless. This kind of access has the potential to significantly alter conditions in locations like Chirasi and Milak Lachchhi. A universe of knowledge that many pupils in these areas do not currently have would become available to them. It would also equip students with the abilities necessary to thrive in the modern digital environment. Technology integration in the classroom could help these kids catch up to, and even outperform, their urban peers, providing them with the opportunity to succeed in the future.

2. Views from the community on educational technology

We heard a great deal of optimism from teachers and parents. Parents care a great deal about their kids' futures and believe that technology can help level the playing field. They want their children to enjoy the same opportunities as their urban counterparts. Although they require the appropriate tools and training, teachers are also keen to use technology to enhance their classes. The thing that most impressed me was how willing everyone was to pick up new skills and adjust. They merely require the correct resources and assistance to fulfill their ambition to get better. If given the opportunity, people are willing to work hard for things like reasonably priced gadgets, dependable internet, or teacher training.

3. Challenges in promoting technology for inclusive education

A major obstacle is the absence of infrastructure; many of these settlements lack reliable internet or energy connections, making the use of digital tools in the classroom nearly difficult. Additionally, neither teachers nor pupils are proficient in digital tools. The procedure is slowed considerably by the fact that many people are not proficient with devices. Then there is the price. Most families are unable to take advantage of these opportunities because they lack the funds to purchase equipment or pay for internet access. However, there is optimism despite these obstacles. People in the neighborhood are looking for answers, such as affordable digital solutions that could have an impact or community learning centers with shared resources. They only require assistance to make it happen, but the willingness is there.

4. Broader implications

The events in Chirasi and Milak Lachchhi are not exclusive to these communities. India's rural inhabitants struggle with access to technology in a similar way. Children in rural places frequently lose out on the same educational chances as children in cities due to a lack of adequate facilities and resources. However, there is a path ahead. Developing solutions that are effective for these particular areas is crucial, whether that means supplying reasonably priced technology, educating educators, or establishing neighborhood support networks. We can guarantee that every child, regardless of where they reside, has the resources they need to thrive if we can coordinate local initiatives with national initiatives like Digital India. Giving every child the chance to realize their full potential is more important than only focusing on technology.

Recommendations

Addressing the complex problems of digital exclusion in rural India requires a multipronged approach that includes community ownership, infrastructural development, human resource capability, and continuous innovation. Each of the following tactics focuses on an important area of intervention and offers a blueprint for long-term, systemic change that benefits entire communities as well as students.

This shift requires long-term planning and grassroots participation. Instead of focusing only on temporary fixes, policymakers must make a commitment to developing strong, adaptable systems. However, the power to identify local needs, set priorities, and work together on educational projects should be delegated to schools, youth organizations, and community-based organizations. These collaborative efforts ensure that the solutions are not only successful but also culturally suitable and generally accepted.

Additionally, technology adoption needs to be seen as part of a broader developmental agenda that includes livelihoods, gender equality, and health, putting education in a holistic framework for rural development. To solve these concerns, a number of parties must operate in concert and in a comprehensive manner. To fully utilize technology in rural education, the following strategies can help:

1. Building better infrastructure

The first step in ensuring that everyone has access to digital education is building the necessary infrastructure. This implies:

- Clean, Reliable Energy: Picture solar-powered schools that maintain computer operations and classroom lighting even in isolated locations where power outages are frequent.
- Affordable Internet Access Everywhere: Imagine how broadband has become as ubiquitous as flowing water, enabling children in remote locations to participate in online courses or stream lessons.
- Long-lasting, robust devices: Schools want laptops and tablets that can withstand rough use from inquisitive children without quickly malfunctioning. We are discussing durable equipment that may be purchased on a small budget.
- Local Tech Support: Imagine a local community repair facility where students can get their broken laptops or tablets serviced quickly and affordably, keeping them connected.

2. Supporting teachers with training

At the center of this change are educators, who require assistance in order to transition to digital classrooms:

- Practical Tech Training: Teachers should be comfortable with digital tools, whether it's making an entertaining history lesson presentation or using an app to assist students with math difficulties.
- Combining Old and New: The objective is to train educators how to combine conventional teaching techniques with technology to create more interesting lessons, not to replace chalkboards.
- Learning Together: Skilled educators can foster a sense of collaboration and mutual development by assisting their colleagues in becoming more at ease with technology.
- Honoring Hard Work: Let's honor teachers with awards and public acknowledgment when they acquire new abilities. It's about supporting others and appreciating their effort.

3. Making tech affordable

Everyone should be able to use technology; it shouldn't feel like a luxury:

- Discounts for Schools and Families: By collaborating with tech firms, we are able to offer reasonably priced gadgets and internet bundles, which enables families to more easily invest in their children's education.
- Shared Tech Hubs: Envision a community center where parents may acquire digital skills or where children can use shared computers to complete their homework.

- Flexible Payment Plans: Families might purchase laptops or tablets by making short, reasonable payments, which would help them feel less excluded from technology.
- Free Internet Zones: Picture public spaces such as parks, libraries, or community centers where people may interact, study, or simply browse the internet for free.

4. Engaging the community

Digital education can be more successful and widely accepted if the entire community supports it:

- Parent workshops: Consider holding events where parents may get together, learn how to utilize an educational software, and gain the confidence they need to assist their children with their online coursework.
- Telling Success Stories: By showcasing local children or families who have benefited from digital learning, you can encourage others to try it.
- Dismantling Barriers: Education campaigns can clarify how digital tools assist instructors rather than replace them. Show people how these tools help them give their children a better start in life.
- Listening to Input: Encouraging teachers and families to express their opinions guarantees that the solutions we develop are effective for them.

5. Modernizing the curriculum

Both the tools we utilize and the way we teach must change:

- Local Language Content: Digital lessons should represent students' culture and daily lives, speaking their language both literally and figuratively.
- Fun and Interactive Learning: Picture children studying history in an interactive game or working through physics ideas in a virtual lab—learning that is enjoyable and participatory.
- Relevance to Real Life: Instruction should be applicable to everyday situations. A scientific project might, for instance, use what kids learn online to address local water problems.
- Feedback-Driven Updates: The greatest people to know what works are teachers and students. Learning is enhanced when the curriculum is updated and pertinent in response to their suggestions.

Conclusion:

The inclusive use of technology holds the key to transforming education in rural India. Its success, however, depends as much on people as it does on infrastructure and technology—creative educators, engaged communities, and policymakers who prioritize equity.

Equality, sustainability, and empathy must be the cornerstones of a comprehensive digital transition. Policymakers must devise policies that consider the diverse conditions of rural regions to guarantee that digital solutions are not universally applicable. It's equally important to support local leadership and empower community members to push for change. When families, educators, and students all feel in charge of the educational process, the transition to digital learning proceeds more smoothly and has a bigger impact. All things considered, inclusive technology acts as a link to a world outside of education.

Even though there is still much work to be done, we can ensure that no child is left behind in the digital age and that the objective of inclusive, equitable education is achieved in every Indian town and area if we continue to be dedicated and work together.

References:

- o Muralidharan, K., & Sundararaman, V. (2013). *The impact of digital technology on educational outcomes: A study of rural schools in India*. *Education Economics*, 21(4), 390-410. https://doi.org/10.1080/09645292.2013.796907

2. Pratham. (2020). *Annual Status of Education Report (ASER) 2020: Technology and Education in Rural India*. Pratham Education Foundation. Available at: https://www.asercentre.org/
3. Sahoo, S. (2018). *Role of mobile learning in enhancing education in rural India: A review*. *International Journal of Innovative Research in Science, Engineering and Technology*, 7(5), 2134-2143. https://doi.org/10.15680/IJIRSET.2018.0705151
4. Chandran, V., & Sharma, A. (2019). *Technology in education: A comparative analysis of urban and rural schools in India*. *Journal of Educational Technology & Society*, 22(4), 90-105. Retrieved from https://www.jstor.org/stable/
5. Khurana, M., & Kumar, A. (2020). *Building digital infrastructure for inclusive education in rural India: Challenges and opportunities*. *International Journal of Education and Development*, 36(6), 405-419. https://doi.org/10.1016/j.ijedudev.2020.03.004
6. Bhat, A. K., & Kaur, P. (2017). *Bridging the digital divide: Mobile technology and education in rural India*. *Journal of Rural Development*, 36(1), 22-40. Retrieved from https://www.jrds.in/
7. Chavan, M., & Arora, V. (2021). *The future of rural education in India: A focus on digital learning*

INTEGRATED RURAL CHALLENGES: A DUAL CASE STUDY ON HEALTH AND EDUCATION IN GREATER NOIDA

Ukashatu Alamin Mohammed, Muhammad Usman Ibrahim, Abdulsamad Umar Sani, Yusuf Abdullahi Sani and Raheel Hassan

Department of Computer Science and Applications,

Sharda University, Greater Noida, U.P. India

*Corresponding author E-mail: raheel.hassan@sharda.ac.in

Abstract:

This book chapter offers a detailed study of two key Sustainable Development Goals (SDGs) within rural India: SDG 3 (Good Health & Wellbeing) and SDG 4 (Quality Education). Based on the two Community Connect visits which went to Milak Lachchhi and Chirasi in Greater Noida, the study explores some critical barriers related to public health and education in underserved communities. Through a blend of quantitative surveys as well as qualitative interviews, we highlight certain systemic issues, like poor healthcare infrastructure, lack of clean water, teacher shortages, plus limited access to secondary education. Several practical recommendations along with a few community-driven solutions are proposed for the purpose of addressing these challenges through sustainable and inclusive development strategies.

Keywords: SDG 3, SDG 4, Rural Development, Healthcare Access, Education Barriers, Milak Lachchhi, Chirasi, Sanitation, Teacher Shortage, Public Health, Digital Divide.

Part 1: SDG 3 – Good Health & Wellbeing in Milak Lachchhi

Introduction:

Good health constitutes a critical element for development that is sustainable. It helps people have good lives and helps communities to be well overall. Sustainable Development Goal 3 (SDG 3) by the United Nations aims to "ensure healthy lives as well as promote well-being for all at all ages." However, rural areas like Milak Lachchhi in Greater Noida, Uttar Pradesh, continue to face quite serious health-related challenges.

In Milak Lachchhi, access to certain basic healthcare, clean drinking water, and proper sanitation is limited for people. Public health infrastructure is indeed poor, and also awareness programs are minimal or absent. These issues have resulted in waterborne diseases, and frequent illness has followed. They have also resulted in poor hygiene practices, especially open defecation. Children are the most affected group; many are missing schools on account of sickness. This impacts their education, and it also impacts future opportunities.

As a segment of a Community Connect plan, fieldwork happened in that village to grasp such issues better. We found a gap that was major between health services available and needs of the community, via surveys, observations, and interviews. This gap is not just about infrastructure as well as about a certain lack of health education, limited government support, and poor implementation of health schemes.

Many villagers understand the importance for clean water and hygiene, but lack sufficient resources or support for action. Healthcare workers rarely visit, in addition preventive care is almost non-existent. Therefore, folks have to try and cope by themselves or get costly private care, which then stretches what little money they have.

Methodology:

The study was conducted in Milak Lachchhi, a rural village located in Greater Noida, Uttar Pradesh. This location was selected due to its limited access to healthcare and sanitation facilities, making it a relevant case for examining health-related challenges in underserved areas.

Data collection involved a mix of quantitative and qualitative methods:

- Household surveys were conducted with over 100 families to gather data on health conditions, water sources, sanitation facilities, and hygiene practices.
- Field observations helped verify the physical environment, including the availability of toilets, waste disposal systems, and water quality.
- Informal interviews were held with community members, local health workers, and school teachers to gain insights into health awareness, government support, and barriers to healthcare access.

The study focused on identifying practical gaps and community readiness for health interventions.

Key Findings:

The study uncovered several critical health, sanitation, and hygiene challenges faced by the residents of Milak Lachchhi village:

- Approximately 65% of the households do not have access to toilets in their home. Open defecation continues widely, especially where families cannot construct private toilets due to a lack of space or resources. This practice affects personal dignity and leads to environmental, health consequences of severity.
- The village depends mostly on handpumps for its drinking water, and also on shallow wells. A lot of these water sources happen to be contaminated with coliform bacteria because of maintenance that is improper, as well as their being near waste dumping areas and also open defecation zones. This contamination puts residents at a continuous risk for consuming unsafe water.
- Many cases of waterborne diseases, inclusive of diarrhea, typhoid, skin infections, with respiratory issues, were reported, notably during the monsoon season, when water

stagnation together with flooding each make conditions worse. These illnesses impact many adults and children alike.

- Waste disposal practices are greatly poor. Most of the households will burn waste, or they dispose of waste in open fields or in drains. This pollutes not only the local environment but also increases presence of flies, mosquitoes, and rodents, which spread disease further.
- School attendance among children is frequently disrupted. This situation occurs due to some recurring health issues. Absenteeism relating to illness, without a doubt, directly affects their academic performance and long-term educational outcomes.
- Despite these few challenges, there is a growing awareness as well as willingness among villagers to explore more solutions. Many interests were voiced for rainwater harvesting systems, low-cost decentralized sanitation units, and health awareness programs, provided technical assistance and financial support are received.

Discussion:

The health challenges observed in Milak Lachchhi point to serious gaps inside the village's ability for meeting several core targets under Sustainable Development Goal 3 (SDG 3). Even with various national initiatives and schemes focused on improving rural healthcare, the village still struggles with its basic sanitation, clean water access, and proper healthcare delivery. This disconnects between policy and practice surely needs instant attention.

The most visible shortfall relates to Target 3.3, that is the one focusing on reduction of waterborne diseases. The common usage of the contaminated water sources, plus open defecation, and also poor waste disposal all have led to some recurring health issues such as just diarrhea, typhoid, and even skin infections. The monsoon season worsens the situation, for waterlogging, in addition to runoff, spreads infections more quickly.

Target 3.4, a goal that calls for preventive healthcare strengthening in addition to health education promotion, also remains unfulfilled. The goal stays unfulfilled. There is limited access for structured health education within the village. A number of residents are aware of hygiene-related issues but lack the tools, resources, or support to reach well-educated, consistent decisions. This curtails lasting changes.

Target 3.8, with targeting for universal health coverage, appears distant. The health centers that are nearest are far and also under-resourced. Healthcare is frequently provided by informal practitioners lacking regulation or adequate qualifications. Health services are mostly reactive, as opposed to preventive.

Core barriers include:

- Financial hardship: Most villagers cannot afford toilets, water filters, or transport to urban health centers.

- Weak delivery of government programs: Initiatives like Swachh Bharat and Ayushman Bharat have not reached or impacted this village in a meaningful way.
- Cultural resistance: Older generations often resist changes in hygiene practices. Open defecation and unsafe water habits persist due to generational habits.
- Lack of skilled local leadership: The absence of trained local health workers or volunteers contributes to the persistence of these issues.

Recommendations:

To address the multi-layered issues found in Milak Lachchhi, a set of comprehensive and localized recommendations is needed. These should focus on practicality, sustainability, and community ownership.

1. Sanitation Infrastructure Development

- Construct community toilets with bio-digester technology to reduce environmental impact.
- Offer partial subsidies or microloans for households to build private toilets.
- Appoint and train local sanitation workers for maintenance and monitoring.

2. Safe Water Access

- Install village-level water purification systems that filter handpump and well water.
- Distribute household-level water purification tablets or filters, especially before monsoon season.
- Conduct monthly water safety tests and publish the results publicly.

3. Mobile and Local Health Services

- Launch monthly mobile health clinics with qualified medical staff for regular checkups and medicine distribution.
- Set up a basic health sub-center within the village with a trained community health volunteer for minor cases and referrals.

4. Health Education Campaigns

- Partner with NGOs and schools to conduct monthly awareness drives on handwashing, menstrual hygiene, nutrition, and child care.
- Use visual materials, posters, and street plays in the local language to increase participation.
- Involve women’s groups, school teachers, and students as health ambassadors.

5. Capacity Building

- Train village youth in sanitation technology, water testing, and community outreach.
- Form a village health and hygiene committee to monitor progress and engage with local authorities.

- Provide incentives for local participation in public health efforts, such as free health checkups or ration benefits.

6. Policy Support and Monitoring

- Involve the district health office in quarterly monitoring and review meetings.
- Invite private companies under CSR initiatives to sponsor toilets, water systems, and health awareness programs.
- Create a feedback system where villagers can report issues anonymously through SMS or suggestion boxes.

Part 2: SDG 4 – Overcoming Educational Barriers in Chirasi

Introduction:

Education plays a vital role in individual empowerment as in social progress. The United Nations Sustainable Development Goal 4 (SDG 4) advocates quality education for all inclusively and equitably, with emphasis on opportunities for lifelong learning. However, rural areas, such as Chirasi, found in Greater Noida, still continue to face barriers to achieving the goal. Throughout our field visit, we observed many challenges, as well as limitations to educational access and quality.

Only one government school in the village educates up to Grade 6, so students must travel far for more schooling, but many families cannot afford this. Other big challenges include teacher shortages and inadequate infrastructure and also language barriers, in subjects taught in Hindi and English, especially while the local dialect is commonly spoken. Additionally, gender disparities and socio-economic constraints jointly contribute to early dropout rates, particularly for girls.

Many students come from economically disadvantaged families where education is not prioritized over pressing financial needs. This limits, in effect, the potential for upward mobility and perpetuates cycles of poverty. Our visit targeted at assessment of these exact barriers, in more detail through both surveys and interviews, with a true goal of identification of tailored solutions that fully meet the very specific needs of that community and enable much better access to the education for absolutely all.

Methodology:

Location: Chirasi, Greater Noida

To understand the educational challenges within Chirasi, we employed a combination of qualitative and quantitative research methods. For the purpose of gathering understandings into perspectives on education, we conducted more than 20 interviews with students as well as parents in addition to teachers. Classroom observations helped for us to assess teaching quality and engagement within the school environment. Surveys, in addition, were distributed to several local families to gather data on access to education, household priorities, and socio-economic factors.

We held informal focus group discussions with community members, too. These discussions explored local concerns, needs, and aspirations regarding education.

The key focus areas of our study included:

- School infrastructure
- Teacher availability
- Curriculum breadth
- Language skills
- Dropout rates
- Aspirations of students

Key Findings:

1) The only government school in Chirasi, it serves over 100 students, but it is under-resourced.
   a. Classrooms overcrowded due to space insufficiency.
   b. Teaching methods, now somewhat outdated, rely mainly on chalkboards along with older materials.
2) The school lacks several important facilities toward effective learning:
   a. There is no library for reading or for research.
   b. An absence of a science lab, as well as computer access, constrains practical learning, plus digital literacy.
3) The curriculum is limited to necessary subjects:
   a. Math, English, Hindi, Science, and Social Studies too.
   b. Lack of subjects like Computer Science, arts, or vocational training, limiting students' skill development.
4) Comprehension of English for nearly all students is almost nothing.
   a. Most of the students speak Hindi at home, and battle in reading, writing, and comprehension in English.
5) Dropout rates do sharply increase after Grade 6 owing to:
   a. Absence of several local secondary education options.
   b. Travel is difficult to nearby towns, because further schooling is often unaffordable.
6) Female students are especially at risk of dropping out due to:
   a. Traveling far for school has cultural and safety-related restrictions.
   b. Customary gender roles are those that prioritize domestic responsibilities for girls.

Discussion:

The educational challenges faced in Chirasi stand as barriers to the targets in SDG 4. Specifically, the limitations with infrastructure, curriculum, and also resources directly impact key goals such as those for universal primary and secondary education (Target 4.1), and equal accessibility to vocational training (Target 4.3), together with gender equality in education (Target 4.5). These challenges prevent students from accessing quality education; additionally, such challenges obstruct skill development necessary for future success.

SDG 4 Alignment:

The absence of infrastructure, like libraries, computer labs, as well as science equipment, limits students' learning experiences, even as it violates Target 4.1, which is about the need for accessible education. The lack of vocational training options directly hampers Target 4.3. Students, being unable to gain practical skills, cannot secure meaningful employment. Gender disparity is additionally obvious, as female students are likelier to drop out due to safety concerns and cultural norms, which poses a challenge in meeting Target 4.5.

Structural Deficiencies:

The lack of government investment in school infrastructure still remains as one of main obstacles. The school's basic facilities, such as classrooms as well as teaching materials, are insufficient for effective learning. The lack of teacher training programs, as well as modern teaching tools, worsens the problem. The issue is thereby magnified. As a result, many students are not receiving the education that prepares them for certain modern challenges.

Community Insights:

Despite these same difficulties, in interviews of students and their parents was revealed a desire for a better education. Parents want their children to get more education, but these dreams are unfulfilled because they lack resources, transportation, and quality secondary education. The community exhibits willingness for the support of education; however, systemic barriers remain. These include financial constraints as well as logistical challenges, all of which require focused solutions.

Recommendations:

To address the educational deficiencies in Chirasi, a multi-faceted approach is necessary for enhancement of infrastructure, improvement to the curriculum, as well as support for students and teachers. The following are several key recommendations;

1) **Build Additional Classrooms and Equip Schools with Modern Learning Tools:** Given the overcrowding of classrooms, it is important for expanding the school infrastructure. Building further additional classrooms would accommodate additional students and reduce much overcrowding. Equipping the school with science kits is necessary, as well as with modern learning tools like computers and digital projectors. These resources would, in fact, enable some interactive learning, also help develop further digital literacy, and then foster the critical thinking among students.

2) **Offer English Language Enhancement Programs and Bridge Courses:**
English skill stands as one of the main barriers against students' academic success. Therefore, implementing English language enhancement programs would improve most of their reading, writing, and speaking skills. Bridge courses additionally aim at filling educational gaps for students. These courses would support students as they transition to secondary education in overcoming learning challenges, especially in subjects like English and Math.

3) **Start Local Scholarships and Provide Free Transportation Facilities:**
The lack of local secondary education options is a cause for many students to drop from out. To alleviate this, with the introduction of local scholarships, education would become more affordable as well as accessible. These scholarships might cover a number of school fees. They also could cover books and transportation costs. Additionally, certain free transportation services, like school buses or travel stipends, would help students travel to secondary schools, reducing the financial burden and travel-related barriers.

4) **Encourage Formation of Parent-Teacher Associations (PTAs) and Empower Community-Based Education Monitoring Groups:**
To increase community involvement in education, the forming of a Parent-Teacher Association (PTA) would encourage collaboration between parents as well as teachers. This partnership can ensure education of priorities reflecting community of needs. Establishing certain community-based education monitoring groups would allow local residents to take a role overseeing school performance. It would address challenges and ensure resources are allocated properly.

5) **Encourage Vocational and Skill Development Programs:**
Introducing vocational as well as skill-based training programs would help students acquire practical skills alongside their academic education. These programs could be tailored for meeting local demands, providing students the opportunity for skills in fields like agriculture, craftsmanship, and technology. Through the incorporation of vocational education within the school curriculum, students would each have the option to then pursue careers. Said careers do not necessarily require higher education; instead, those careers are vital for local economic development.

General Conclusion

The visits to Milak Lachchhi and Chirasi have provided some deep understandings into just the two fundamental SDG gaps which rural communities do face: access to health and education. The villages, located nearby urban areas like Greater Noida, battle with infrastructural inadequacies. Economic constraints, in addition to this, obstruct their ability to achieve the

Sustainable Development Goals (SDGs). Even so, notwithstanding such challenges, both communities show a distinct willingness for improving their circumstances. This shows that, with the support and with resources right for them, rural areas can make meaningful strides toward achievement of SDG targets related to health and to education.

Health and Education Gaps

In Milak Lachchhi, basic healthcare services and clean drinking water are still limited, contributing to poor sanitation and a high prevalence of waterborne diseases. In like manner, Chirasi faces educational disparities, along with a school infrastructure that is quite limited and no real secondary education options. These deficits immediately affect the well-being and later outlook of people within communities, forming a harmful pattern of hardship and bleak growth results. To depict, the deficiency of adequate sanitation within Milak Lachchhi worsens health issues. Likewise, the insufficiency of wide-ranging education throughout Chirasi curtails the community's upward mobility, thereby retaining children situated into a cycle of poverty.

Community Willingness and Potential for Change

A main point from the two studies is how the community is willing to take part in change. Those residents of Milak Lachchhi are receptive to the solutions, like rainwater harvesting, along with decentralized sanitation systems, provided that they do receive technical and financial support. Likewise, the parents and students throughout Chirasi are quite motivated toward improving educational prospects yet face certain barriers like infrastructure lack and access limits to secondary education of quality. This willingness is indeed a valuable asset, as it suggests that those interventions designed with active participation of the community are much more likely to then succeed. Engaging local residents in the decision-making process encourages a sense of ownership. It also ensures that solutions are contextually relevant and sustainable.

The Role of Grassroots Planning, Government, and NGOs

To bridge these gaps, a grassroots planning is important. While local knowledge is necessary in identifying the real needs and priorities, government support is necessary in order to provide the structural and financial resources needed for implementing larger-scale interventions. Government programs can play a role in Milak Lachchhi and Chirasi, such as Swachh Bharat Abhiyan and educational initiatives. However, there is a need for better implementation and monitoring to effectively reach the marginalized areas. NGOs have a vital role to play, for example, in offering technical expertise, financial resources, plus hands-on guidance. For example, NGOs can help to design sanitation solutions, off vocational training, as well as provide the needed resources to improve educational infrastructure.

Lasting changes will be most effective using a collaborative approach with NGOs, the government, and the community. The degree of willingness that community members have to engage, along with the support that external organizations provide, can accelerate progress in achieving SDGs.

Custom Interventions for Rural Advancement

Our dual case study underscores an important point: rural advancement with itself is not a one-size-fits-all model. The applicable solutions for one community may not essentially work for another. This is on account of the distinct challenges and resources that each community possesses. Milak Lachchhi requires solutions specific to its health challenges, such as water purification as well as waste management, while Chirasi needs infrastructure coupled with secondary education options for breaking the cycle of limited educational opportunities. Interventions must be somewhat customized and grounded in the specific local needs and realities of each community.

Conclusion:

In conclusion, the SDG gaps in health as well as education observed in Milak Lachchhi and Chirasi highlight important challenges faced by rural communities. However, these challenges are nearly insurmountable. These communities can overcome their barriers through grassroots planning. There is also strong government support, as well as the involvement of NGOs. More importantly, the active willingness of the communities for contribution to solutions indicates that rural advancement is achievable. Through specified interventions, the rural areas have possibilities to move near to reaching SDG targets, in the process creating some future for those residents.

References:

1. World Health Organization (2023). "Sanitation and Health." [www.who.org]
2. UNICEF (2022). "Water, Sanitation and Hygiene in Schools."
3. UNESCO (2023). "Global Education Monitoring Report."
4. Government of India (2021). Swachh Bharat Mission Guidelines.
5. UNDP (2023). Sustainable Development Goals Indicators.
6. Gavi, the Vaccine Alliance. (2022). Immunization Progress Reports.
7. National Institute of Rural Development. (2023). Reports on Rural Schooling Infrastructure.
8. WHO. (2023). Mental Health and Community Wellbeing Reports.
9. Indian Ministry of Education. (2022). Annual Educational Status Report (ASER).
10. Rao, V. (2022). "Educational Inequity in India: Structural Challenges and Reforms." Journal of Rural Studies.

THE IMPACT OF CLIMATE CHANGE IN RURAL AREAS

Matthews Manuel Mphinga, Luke David Jailosi,

Yamikani Chikaipa, and Frank Issa and Raheel Hassan*

Department of Computer Science and Applications,

Sharda University, Greater Noida, U.P. India

*Corresponding author E-mail: raheel.hassan@sharda.ac.in

Abstract:

The impact of climate change on rural communities is increasingly evident, with significant consequences for agriculture, livelihoods, water availability, health, and disaster preparedness. A field survey conducted in Chirasi and Milak Lachchhi villages in Greater Noida reveals that farmers are experiencing reduced crop yields and heightened uncertainty due to irregular rainfall patterns. Economic hardships are deepening, as traditional livelihoods become less viable under shifting climatic conditions, forcing changes in farming and occupational practices. Water bodies are reportedly drying more frequently, indicating gradual degradation of water resources, though drinking water shortages remain relatively mild. Rising cases of heat-related illnesses highlight escalating health vulnerabilities, while the absence of disaster response plans and training exposes critical gaps in community resilience. These findings underscore the urgent need for targeted policy interventions, capacity-building initiatives, and sustainable development strategies that are tailored to the specific vulnerabilities of rural populations.

Keywords: Climate Change, Rural Communities, Agriculture, Livelihoods, Water Resources, Health Impacts, Disaster Preparedness, Greater Noida, Community Resilience, Environmental Adaptation.

Introduction:

Climate change poses one of the most pressing challenges of our time, with its effects being felt most acutely in vulnerable rural communities. These areas, often dependent on agriculture and natural resources for their livelihoods, face disproportionate risks due to their limited adaptive capacity and infrastructural support. In India, rural populations are experiencing the tangible consequences of rising temperatures, erratic rainfall, and extreme weather events. This study focuses on the villages of Chirasi and Milak Lachchhi in Greater Noida, where a survey was conducted to assess how climate change is affecting daily life. The research explores impacts across five key areas: agriculture, livelihood, water resources, health, and disaster preparedness. By capturing local perceptions and experiences, the study aims to provide insights into the groundlevel realities of climate stress and to highlight the urgent need for inclusive, grassroots-level responses to build resilience in rural settings.

Survey Locations and Methodology:

The survey was conducted in two rural villages located in the Greater Noida region of India: Chirasi and Milak Lachchhi. These areas were selected due to their reliance on agriculture, vulnerability to environmental shifts, and limited access to institutional support—making them ideal for assessing the grassroots impacts of climate change.

A quantitative survey approach was employed, involving a structured questionnaire consisting of 10 yes/no questions. These questions targeted five key thematic areas: agriculture and farming, livelihood and economy, water resources, health and well-being, and disaster preparedness. The questions were designed to elicit direct, experience-based responses from the community members regarding observable climate-related changes and their effects on daily life.

Methodology:

Participants were selected through a simple random sampling method within the villages, ensuring a diverse representation of age, occupation, and gender. Respondents included small-scale farmers, daily-wage workers, homemakers, and elders. The survey aimed not only to document observed environmental changes but also to understand community-level awareness and preparedness regarding climate-related risks.

The responses were then compiled and analyzed to identify common trends, vulnerabilities, and gaps in resilience. The methodology was deliberately kept accessible and participatory, enabling a more accurate reflection of the lived experiences of those directly impacted by climate variability.

Visit 1: Milak Lachchhi Village

The first field visit took place in Milak Lachchhi, a rural village in Greater Noida characterized by its dependence on agriculture and traditional livelihoods. The research team engaged with local residents to gather firsthand accounts of how climate change is affecting their daily lives. During this visit, villagers reported noticeable changes in weather patterns, particularly irregular and unpredictable rainfall, which has made traditional farming increasingly difficult. Many respondents confirmed a decline in crop yields over recent years, attributing it to erratic monsoons and prolonged dry spells. The majority also expressed concern over the economic impact, noting that reduced agricultural output has directly affected household income and forced some to seek alternative forms of employment.

In terms of water resources, villagers observed that local ponds and water bodies have started to dry up more frequently, though issues with drinking water availability were less severe at the time of the visit. Health-wise, several residents highlighted a rise in heat-related illnesses, especially among the elderly and children, indicating growing vulnerability to high temperatures. One of the most critical findings was the lack of awareness and preparedness for climate-related disasters. The community did not have a formal disaster response plan, nor had most residents received any training to handle emergencies such as floods or droughts. Overall, the visit to Milak Lachchhi provided valuable insights into the direct, on-the-ground impacts of climate change on a vulnerable rural population and underscored the need for targeted support in climate adaptation and resilience building.

Visit 2: Chirasi Village

The second field visit was conducted in Chirasi Village, also located in Greater Noida, where the research team continued its investigation into the effects of climate change on rural communities. Like Milak Lachchhi, Chirasi is an agrarian settlement heavily dependent on seasonal rainfall and natural water sources for both farming and daily living. Residents of Chirasi reported a moderate but consistent decline in crop yields, citing irregular rainfall as the primary cause. Many shared experiences of planting cycles being disrupted by unexpected dry periods or untimely rain, which has negatively impacted food security and income stability. Some farmers have had to alter their cropping patterns or adopt less water-intensive crops, indicating early adaptation efforts driven by necessity. With regard to livelihoods, the community expressed concern over the growing difficulty of sustaining income from agriculture alone. This has led some individuals to explore alternative jobs in nearby urban areas, increasing migration trends during off-seasons.

In terms of water availability, the villagers noted that while drinking water was still generally accessible, nearby water bodies such as small lakes and canals have been drying up more frequently, raising alarms about long-term sustainability. Health-related issues were also prominent in Chirasi, with respondents pointing to an increase in heat-related ailments, particularly during the summer months. However, most people reported that access to healthcare services remained stable, even during extreme weather events. Importantly, Chirasi—like Milak Lachchhi—lacked formal disaster preparedness measures. There were no community-wide response plans, and very few residents had received any training on how to deal with events like floods, droughts, or heatwaves. This visit reaffirmed the patterns observed in the previous village and highlighted a recurring theme: climate change is subtly but steadily eroding rural resilience, and without structured interventions, these communities will remain highly vulnerable to environmental and socioeconomic shocks.

Contrasting Insights:

The field visits to Milak Lachchhi and Chirasi villages revealed several commonalities in how climate change is affecting rural communities, but also brought forward distinct differences in experiences and adaptation responses.

Similarities:

- Agricultural Impact: Both villages reported a decline in crop yields and difficulties caused by unpredictable rainfall. This common challenge has led to increased agricultural uncertainty and reduced food security.
- Livelihood Strain: Residents in both locations confirmed that climate change has negatively affected income from farming, with some individuals forced to change their occupation or agricultural practices.
- Water Body Depletion: While drinking water shortages were not severe in either village, both reported that local water bodies were drying up more frequently, indicating a long-term stress on water resources.
- Health Concerns: There was a notable increase in heat-related illnesses in both communities, reflecting the growing health burden of rising temperatures.
- Lack of Preparedness: Neither village had an active disaster response plan or training programs to deal with climate-related emergencies such as floods or droughts.

Differences:

- Adaptation Efforts: Chirasi showed signs of early adaptive behavior, with some farmers experimenting with less water-intensive crops or modified planting schedules. In contrast, Milak Lachchhi appeared to be in a more reactive phase, with fewer changes implemented.
- Migration Trends: While both communities face economic pressure, Chirasi had more evidence of seasonal migration to nearby towns in search of alternative income, suggesting a higher level of socio-economic mobility.
- Health Access: Residents in Chirasi reported more consistent access to healthcare, even during extreme weather, whereas in Milak Lachchhi, health infrastructure was less accessible, increasing vulnerability during climate events.

These contrasting insights highlight the diverse ways rural communities experience and respond to climate change, depending on local resources, awareness, and institutional support. Understanding these nuances is crucial for designing context-specific policies and interventions that strengthen resilience where it is needed most.

Discussion:

The findings from Milak Lachchhi and Chirasi villages illustrate the multi-dimensional impact of climate change on rural communities and provide a compelling case for deeper engagement with vulnerable populations. The consistency of climate-related challenges—such as reduced crop yields, economic instability, and drying water bodies—highlights the systemic nature of the issue. These changes are not isolated but interconnected, with agricultural stress leading to financial hardship, which in turn exacerbates health vulnerabilities and undermines disaster resilience. One critical insight is the lack of institutional support and community preparedness. Despite increasing exposure to extreme weather events, both villages showed minimal readiness in terms of disaster response planning or training. This gap in preparedness not only increases the risk of loss during climate events but also delays recovery, especially in resource-scarce environments. The subtle differences in adaptive behavior—such as crop diversification in Chirasi or the early signs of migration for alternative livelihoods—indicate that local context plays a key role in shaping responses. These grassroots strategies, though limited, demonstrate the potential for communityled adaptation, provided adequate support systems and awareness programs are in place.

Furthermore, the rise in heat-related illnesses across both villages points to the emerging health crisis linked to climate change. While Chirasi's better access to healthcare offers some resilience, Milak Lachchhi's limited facilities present a serious concern. This disparity underscores the need for integrating climate resilience with rural health planning. Overall, the discussion emphasizes that while climate change is a global phenomenon, its impacts are deeply local, demanding tailored solutions that account for the social, economic, and environmental characteristics of each community. Strengthening climate education, investing in resilient infrastructure, and enabling local governance structures are essential steps toward building adaptive capacity and long-term sustainability in rural regions.

I. Impact of Climate Change: The survey findings from Milak Lachchhi and Chirasi villages in Greater Noida demonstrate the wide-ranging and compounding impacts of climate change on rural life. These impacts manifest across critical areas that sustain the daily functioning and long-term well-being of communities:

1. Agriculture and Food Security:

Farmers in both villages reported a decline in crop yields due to increasingly unpredictable rainfall patterns and prolonged dry spells. Traditional planting schedules are being disrupted, leading to lower productivity and reduced reliability of seasonal harvests. This has directly threatened food security and income stability, particularly for smallholder farmers.

2. Livelihood and Economic Vulnerability

Agriculture being the primary source of livelihood in these villages, any disturbance in climatic conditions has an immediate economic consequence. Households face reduced income, and some have been forced to seek alternative jobs or migrate temporarily to urban areas. This transition is often unplanned, placing additional stress on already fragile rural economies.

3. Water Resources

While drinking water shortages were not yet critical, the frequent drying up of local water bodies is a clear signal of gradual water resource depletion. This has implications not only for household needs but also for irrigation, livestock, and sanitation—especially during peak summer months.

4. Health and Well-being

Climate change is contributing to a noticeable increase in heat-related illnesses, including dehydration, heatstroke, and fatigue, particularly among vulnerable groups such as the elderly and children. Rising temperatures and changing weather patterns are slowly emerging as public health threats in rural settings.

5. Disaster Preparedness

The villages lack formal disaster response plans and community training programs, leaving them highly exposed to risks from floods, droughts, and other extreme events. This lack of preparedness severely limits the communities' ability to respond to and recover from climate-related disasters, increasing their overall vulnerability.

In summary, the impact of climate change in these rural areas is multi-sectoral and deeply interconnected. It is not only degrading the natural resource base but also intensifying socioeconomic stress, undermining public health, and exposing critical gaps in resilience infrastructure. Without timely interventions, these challenges are likely to deepen, threatening the long-term sustainability of rural livelihoods.

II. Community Perspectives on Climate Change

The voices from Milak Lachchhi and Chirasi villages offer a grounded and insightful view of how rural communities perceive and experience climate change. These perspectives, shaped by lived realities rather than scientific data, reflect both the awareness of environmental change and the struggle to cope with its effects.

1. Awareness Through Experience

Most villagers did not refer to "climate change" in scientific terms, but they clearly recognized shifts in weather patterns, such as irregular rainfall, longer dry spells, and rising temperatures. These observations were often linked to visible outcomes—declining crop yields, drying ponds, and more frequent illness. For them, climate change is not a future threat—it is a current reality.

2. Sense of Helplessness

Many respondents expressed a feeling of helplessness in the face of these changes. With little access to reliable weather information, agricultural support, or financial safety nets, they felt illequipped to respond. This lack of control over both their environment and the means to adapt has fostered a sense of vulnerability and frustration.

3. Adaptation Under Constraint

While some community members in Chirasi have begun experimenting with altered cropping patterns or off-farm jobs, these adaptations are often reactive and resource-constrained. There is interest in change, but limited knowledge, capital, and institutional support restrict the community's ability to respond effectively.

4. Desire for Support and Training

Despite limited formal education on climate issues, there is a strong interest in learning how to cope better. Community members expressed a clear desire for government-led training programs, weather advisories, and disaster preparedness support. They want solutions that are practical, accessible, and tailored to their specific challenges.

5. Local Wisdom and Resilience

Traditional knowledge, such as reading weather cues from natural signs, still plays a role in decision-making. However, many acknowledge that climate patterns are changing too rapidly for old methods to remain reliable. This intersection of traditional knowledge and modern uncertainty marks a critical point where external support can empower local resilience.

In essence, community perspectives highlight that rural people are aware, concerned, and willing to act—but are severely limited by a lack of resources, information, and institutional backing. Their insights reinforce the urgent need for inclusive, community-centered climate policies that build resilience from the ground up.

III. Diverse Challenges in Promoting Climate Change Awareness

Efforts to promote climate change awareness in rural areas such as Milak Lachchhi and Chirasi villages face a range of diverse and interlinked challenges. These barriers span educational, cultural, infrastructural, and economic dimensions, all of which hinder the effective dissemination and acceptance of climate knowledge at the grassroots level.

1. Limited Scientific Literacy

Many community members have low levels of formal education, making it difficult to understand climate change in abstract or scientific terms. Concepts such as “global warming,” “carbon emissions,” or “greenhouse gases” often feel distant or irrelevant when compared to immediate, daily struggles such as low crop yields or lack of income. This gap makes it necessary to translate climate knowledge into relatable, local narratives.

2. Mismatch Between Global Messaging and Local Realities

Climate awareness campaigns often rely on generalized global narratives that fail to connect with rural lived experiences. Villagers are more responsive to tangible examples—such as changes in rain timing or increase in summer heat—rather than broad warnings about melting glaciers or sealevel rise. The disconnect between messaging and daily realities reduces the perceived urgency and importance of climate action.

3. Information Access and Communication Channels

There is a lack of accessible communication infrastructure in rural areas. Internet penetration is low, media access is limited, and official information on weather or adaptation strategies often does not reach the villages. Traditional channels—like community meetings or radio—are underused or inconsistently utilized, making it hard for accurate and timely climate information to circulate.

4. Cultural Beliefs and Local Priorities

In some cases, changes in weather or agriculture are attributed to superstition, divine will, or fate, rather than environmental causes. These cultural beliefs can compete with scientific explanations and limit the effectiveness of awareness efforts unless communication strategies are culturally sensitive and engage with existing belief systems.

5. Economic Insecurity as a Barrier

For many rural families, survival takes precedence over sustainability. When communities are struggling to meet basic needs, long-term planning or environmental awareness becomes secondary. Promoting climate literacy without addressing underlying poverty may result in resistance or apathy.

6. Lack of Local Role Models or Champions

Awareness campaigns are often more successful when driven by local leaders or respected community members. However, many villages lack trained individuals who can bridge the gap between scientific knowledge and local understanding, leaving a leadership vacuum in grassroots climate education. In summary, promoting climate change awareness in rural settings requires context-sensitive approaches that are grounded in local language, culture, and priorities. Bridging knowledge gaps, empowering local facilitators, and integrating awareness into livelihood support and health services can help overcome these diverse challenges and build a foundation for long-term climate resilience.

IV. Recommendations

Based on the findings from Milak Lachchhi and Chirasi villages, several actionable recommendations can be made to enhance climate resilience and awareness in rural communities. These recommendations focus on addressing the interconnected challenges of environmental degradation, socio-economic vulnerability, and knowledge gaps:

1. Community-Based Climate Education Programs

Design and deliver localized awareness campaigns using vernacular languages and relatable examples.

- Use interactive methods such as street plays, visual aids, and community radio to improve engagement.
- Integrate traditional knowledge with scientific insights to build trust and relevance.

2. Strengthen Agricultural Support and Training

- Provide training in climate-resilient farming practices, including crop diversification, soil conservation, and water-efficient irrigation techniques.

- Facilitate access to weather forecasts and seasonal advisories to help farmers plan more effectively.
- Support the formation of farmer collectives or cooperatives to share knowledge and reduce vulnerability.

3. Improve Water Resource Management

- Promote rainwater harvesting and the restoration of local water bodies to ensure long-term water security.
- Support community-led monitoring of water usage and promote water conservation practices in households and farms.

4. Enhance Rural Health Infrastructure

- Develop climate-sensitive health programs, focusing on heat-related illnesses, nutrition, and mental health.
- Ensure rural health centers are equipped to function during extreme weather events, including through solar power and emergency supplies.

5. Build Disaster Preparedness and Response Capacity

- Develop and implement community-level disaster management plans tailored to local risks (floods, droughts, heatwaves).
- Conduct regular training and simulation exercises in partnership with local authorities and NGOs.
- Equip villages with early warning systems and basic emergency kits.

6. Facilitate Livelihood Diversification

- Provide skill development programs and microfinance opportunities to help rural households diversify income sources.
- Support women and youth in accessing alternative livelihoods such as small businesses, digital services, or renewable energy jobs.

7. Policy Integration and Government Support

- Advocate for integration of climate resilience into rural development policies at the district and state levels.
- Ensure that schemes like MGNREGA, rural electrification, and agricultural subsidies are climate-smart and equitably accessible.

These recommendations emphasize the need for a multi-sectoral and participatory approach to climate adaptation—one that empowers rural communities with knowledge, tools, and institutional support to manage climate risks and build sustainable futures.

Conclusion:

The field-based study conducted in Milak Lachchhi and Chirasi villages clearly illustrates that climate change is already impacting rural communities in profound ways, particularly through disruptions to agriculture, livelihoods, health, water resources, and disaster resilience. While the scientific discourse around climate change often focuses on global trends, the local realities reveal a more immediate and personal dimension of the crisis—one marked by uncertainty, hardship, and limited adaptive capacity.

Despite the challenges, the study also highlights the resilience and awareness that exist at the grassroots level. Community members recognize environmental changes and express a willingness to adapt, but are constrained by a lack of resources, institutional support, and accessible information. Their perspectives reinforce the importance of inclusive, community-centered solutions that prioritize education, capacity-building, and climate-smart development.

To build true resilience, efforts must go beyond temporary relief or isolated interventions. What is needed is a long-term, integrated approach that combines scientific knowledge, policy support, and local participation. By aligning development strategies with the lived experiences of vulnerable populations, we can begin to close the gap between climate awareness and climate action—ensuring that rural communities are not just passive victims of climate change, but active agents in shaping a more sustainable future.

References:

1. Intergovernmental Panel on Climate Change (IPCC). (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/
2. Ministry of Environment, Forest and Climate Change, Government of India. (2021). *India: Third Biennial Update Report to the United Nations Framework Convention on Climate Change (UNFCCC)*. https://moef.gov.in
3. National Bank for Agriculture and Rural Development (NABARD). (2019). *Climate Resilient Agriculture in India: A Strategy for Transformation*. https://www.nabard.org
4. United Nations Development Programme (UNDP). (2020). *Strengthening Climate Resilience in Rural India: Best Practices and Case Studies*. https://www.undp.org
5. World Bank. (2021). *South Asia Climate Change Strategy*. https://www.worldbank.org
6. Food and Agriculture Organization (FAO). (2020). *Climate-Smart Agriculture Sourcebook*. http://www.fao.org/climate-smart-agriculture

FARM PROFITABILITY THROUGH ENERGY EFFICIENCY: A COMPREHENSIVE ANALYSIS OF SUSTAINABLE AGRICULTURAL BUSINESS MODELS

Sandeep Kumar[1], Harshit Mishra*[2],

Deep Chand Nishad[3], Shivam Srivastav[4] and Kartikay Srivastava[5]

[1]Department of Agronomy, Shri Durga Ji Post Graduate College, Chandeshwar, Azamgarh, 276 128, Affiliated to Maharaja Suhel Dev University, Azamgarh, U.P.

[2]Department of Agricultural Economics, College of Agriculture, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, U.P. 224 229

[3]Department of Agronomy, Shri Durga Ji Post Graduate College, Chandeshwar, Azamgarh (U.P.) -276 128, Affiliated to Veer Bahadur Singh Purvanchal University, Jaunpur, U.P.

[4]Department of Genetics and Plant Breeding, Bihari Lal Smarak Kisan P. G. College, Amadarveshpur, Ambedkar Nagar (U.P.) – 224 139, Affiliated to Dr. Rammanohar Lohia Avadh University Ayodhya, U.P.

[5]Department of Genetics and Plant Breeding, Shri Durga Ji Post Graduate College, Chandeshwar, Azamgarh (U.P.) – 276 128, Affiliated to Veer Bahadur Singh Purvanchal University, Jaunpur, U.P.

*Corresponding author E-mail: wehars@gmail.com

Abstract:

The global sustainable agriculture market was valued at USD 12.09 billion in 2021 and is expected to reach USD 28.91 billion by 2030, growing at a CAGR of 10.17%, driven by consumer awareness and government support. This chapter explores the role of energy efficiency in sustainable agriculture and its impact on farm profitability. Understanding energy consumption in farming is essential, as energy-efficient practices enhance both ecological and economic resilience. Various sustainable agricultural business models are examined, emphasizing their potential to improve profitability through reduced input costs and optimized resource use. Energy-efficient technologies—such as precision agriculture, IoT applications, improved irrigation, and upgraded machinery—are key to optimizing operations. The use of renewable energy sources further strengthens sustainability. Metrics like cost-benefit analysis (CBA) and return on investment (ROI) assess the feasibility of energy-related investments. Government incentives and subsidies play a crucial role in encouraging adoption. Sustainable practices like organic farming, crop rotation, and pest management enhance soil health and biodiversity. Market demand for sustainably produced food creates new opportunities, supported by certification and labelling systems. The chapter also addresses policy frameworks,

environmental regulations, and future governance directions. Overcoming technological, financial, and behavioural barriers through training and awareness programs is essential for a successful transition to energy-efficient farming.

Keywords: Energy Efficiency, Farm Profitability, Renewable Energy, Sustainable Agriculture, Sustainable Business Models

1. Introduction:

The global sustainable agriculture market is expected to grow from USD 13.32 billion in 2022 to USD 31.35 billion by 2031, at a CAGR of 10.17% during the forecast period. The growth of the market is attributed to increasing government initiatives and support for sustainable agriculture practices, growing consumer awareness about the benefits of sustainable food products, and rising demand for organic food (Reis *et al.,* 2021). The global sustainable agriculture market is segmented by input type, crop type, and region. The input type segment is further divided into biofertilizers, biopesticides, biostimulants, and others. Biofertilizers are the largest segment in terms of market share, owing to their increasing adoption by farmers due to their benefits such as improved soil health, increased crop yields, and reduced greenhouse gas emissions (Engler and Krarti, 2021; Tiwari *et al.,* 2011). The crop type segment is further divided into cereals and grains, oilseeds and pulses, fruits and vegetables, and others. Cereals and grains are the largest segment in terms of market share, owing to their wide consumption across the globe (Ulvenblad *et al.,* 2019). The regional segment is further divided into North America, Europe, Asia Pacific, Latin America, and the Middle East and Africa. North America is the largest market in terms of market share, owing to the early adoption of sustainable agriculture practices and the presence of a large number of key players. The major players in the global sustainable agriculture market include BASF SE, Corteva Agriscience, The Mosaic Company, Yara International, and Monsanto Company (Fig. 1). These players are focusing on developing new and innovative sustainable agriculture products and solutions to meet the growing demand from farmers.

In India, the sustainable agriculture market is experiencing rapid growth, primarily fueled by an increasing awareness among consumers about the advantages of sustainable food production and the pressing need to address climate change. Projections indicate that this market is poised to reach $11.7 billion by 2026, with a noteworthy CAGR of 18.5%. The main drivers behind this growth include the rising consumer awareness of the various benefits associated with sustainable food, encompassing health, environmental, and ethical considerations. Moreover, the Indian government is actively promoting sustainable agriculture through initiatives like the National Mission for Sustainable Agriculture (NMSA), the Paramparagat Krishi Vikas Yojana (PKVY), and the Mission for Integrated Development of Horticulture (MIDH). India's favourable climate, abundant in sunshine, water, and arable land, further supports the production of sustainable agricultural products. The key segments within the Indian sustainable agriculture market comprise organic farming, set to reach $6.5 billion by 2026, rapidly expanding precision agriculture, expected to reach $2.5 billion, and the biofertilizers and biopesticides market, forecasted to reach $1.5 billion. Sustainable irrigation systems are also on the rise and projected to reach $1.2 billion by 2026. However, many challenges hinder the market's progress, including the lack of awareness among Indian farmers regarding the benefits of sustainable agriculture, the higher cost of inputs compared to conventional methods, and limited access to markets for their sustainable agricultural products (Tiwari *et al.*, 2023).

The pursuit of sustainable agricultural practices is essential in today's world, where the global population continues to grow, and the strain on natural resources and the environment intensifies. The profitability of farms through energy efficiency has become a crucial topic for researchers, policymakers, and agricultural stakeholders alike (Mushi *et al.*, 2022; Lutsiak *et al.*, 2021). This chapter explores the relationship between energy efficiency and farm profitability, explaining the various aspects of sustainable agricultural business models and offering insights into energy consumption, the role of energy efficiency, and the financial implications of such endeavours. Energy efficiency in agriculture serves as the foundation upon which the subsequent discussions are built. Understanding energy consumption in farming is crucial, and we'll dissect the factors influencing energy use in agriculture (Mishra and Mishra, 2024). These insights will lay the groundwork for comprehending the importance of energy efficiency in farming, which extends beyond cost savings to encompass environmental stewardship and long-term sustainability.

Sustainable agricultural business models are introduced to provide a framework for understanding the principles and characteristics that define them. We explore the various types of sustainable agricultural business models and highlight the multitude of benefits they offer (Mukoro *et al.,* 2022). It is within these models that the integration of energy efficiency practices becomes not only a financial endeavour but also a means to ensure the long-term viability of agricultural operations. As we explore analysing farm profitability, we'll assess the metrics used to measure this critical aspect of agricultural success and emphasize the role energy efficiency plays in enhancing it (De Keyser and Mathijs, 2023). This section will illuminate the intricate connections between energy consumption, cost-effectiveness, and the overall financial health of farms.

Throughout the remainder of this chapter, we'll explore the landscape of energy-efficient technologies for agriculture and their potential for revolutionizing the industry (Mishra and Mishra, 2023). The financial aspects of these technologies will be scrutinized, covering topics such as cost-benefit analysis (CBA), return on investment (ROI), and government incentives and subsidies (Cavazza *et al.,* 2023; Upward and Jones, 2016). Sustainable agricultural practices, market trends, policy considerations, and the various challenges and barriers will also be addressed, offering a comprehensive understanding of the complex dynamics involved in transitioning to energy-efficient farming. Finally, we'll conclude with a discussion on strategies for farm transition to energy efficiency, including the development of energy efficiency plans and the crucial role of training and education. This chapter aims to provide a holistic view of the intricate interplay between energy efficiency and farm profitability, shedding light on the path forward for a more sustainable and economically viable agricultural sector (Ulvenblad, 2021; Kyriakarakos *et al.*, 2020).

2. Energy Efficiency in Agriculture

Energy efficiency in agriculture is a critical component of modern farming practices, contributing to both economic profitability and environmental sustainability. In this section, we will discuss various aspects of energy efficiency in agriculture, including understanding energy consumption in farming, factors influencing energy use, and the importance of adopting energy-efficient practices.

2.1 Energy consumption in farming

Energy consumption in farming refers to the utilization of energy resources to carry out various agricultural operations, from planting and harvesting to processing and transportation (Madau *et al.*, 2020). These energy resources can take various forms, including electricity, diesel fuel, natural gas, and renewable energy sources. Energy consumption in farming is essential for optimizing energy use and identifying areas for improvement (Richter, 2013). The energy consumed in agriculture can be categorized into two primary types:

Direct energy consumption

This category encompasses the energy used in farm machinery and equipment, such as tractors, combine harvesters, irrigation systems, and transportation vehicles. It also includes energy used for heating, cooling, and ventilation in agricultural facilities like greenhouses and storage warehouses.

Indirect energy consumption

Indirect energy consumption in farming relates to the energy used in the production of inputs like fertilizers, pesticides, and seeds. It also considers the energy used in processing and transportation of agricultural products to markets.

Analysing the distribution of energy consumption within these categories is crucial to making informed decisions regarding energy efficiency improvements in agriculture.

2.2 Factors influencing energy use in agriculture

Many factors influence the energy use in agriculture, and understanding these factors is essential to identifying opportunities for optimization. Some factors affecting energy consumption in farming include:

- **Crop and livestock type:** Different crops and livestock require varying levels of energy input for cultivation, such as irrigation, fertilization, and pest control. Understanding the energy demands of specific agricultural activities for different crops and livestock is vital.
- **Farm size and scale:** The size and scale of a farm operation can significantly impact energy use. Larger farms may require more energy for mechanized processes, while smaller farms may have different energy needs.
- **Geographic location:** The climate and location of a farm can influence energy consumption. For instance, farms in regions with extreme weather conditions may require more energy for heating or cooling (Mishra, 2025).
- **Technological adoption:** The level of technology and equipment used in farming operations can affect energy efficiency. Modern, well-maintained machinery tends to be more energy-efficient than older, less efficient equipment.
- **Management practices:** Farm management practices, such as crop rotation, timing of planting, and irrigation scheduling, can impact energy consumption. Efficient management can reduce the overall energy requirements of farming.

2.3 The importance of energy efficiency

Energy efficiency is of paramount importance in agriculture for many reasons:

- **Cost savings:** Adopting energy-efficient practices can significantly reduce operational costs, as energy expenses constitute a substantial portion of a farm's budget. By optimizing energy use, farmers can increase their profit margins.
- **Environmental sustainability:** Agriculture is a significant contributor to greenhouse gas emissions. Energy efficiency measures can reduce the carbon footprint of farming operations, helping mitigate climate change and environmental degradation.
- **Resource conservation:** Energy efficiency in agriculture can help conserve non-renewable resources like fossil fuels, as well as reduce water consumption in irrigation, contributing to long-term sustainability (Mishra and Mishra, 2024).
- **Regulatory compliance:** Many regions have regulations and incentives aimed at reducing energy consumption and promoting sustainable farming practices. Compliance with these regulations is essential to avoid penalties and access financial incentives.

Energy efficiency in agriculture is a multifaceted and critical aspect of sustainable farming practices. Understanding energy consumption, recognizing the factors influencing energy use, and embracing energy-efficient techniques not only enhances farm profitability but also contributes to the broader goals of environmental stewardship and resource conservation (Van Der Wal, 2008; Maturo *et al.,* 2021). This section sets the stage for a more in-depth exploration of energy-efficient agricultural business models in the subsequent parts of the discussion.

3. Sustainable Agricultural Business Models

Sustainable agricultural business models are at the forefront of modern farming practices, emphasizing environmentally responsible and economically viable approaches to food production. In this section, we will discuss the definition, characteristics, types, and benefits of sustainable agricultural business models (Lewandowski, 2016).

3.1 Characteristics of sustainable agricultural business models

Sustainable agricultural business models refer to a holistic approach to farming that integrates environmental stewardship, economic viability, and social responsibility. These models prioritize long-term sustainability over short-term gains and seek to balance the needs of the present without compromising the resources and opportunities available to future generations (Klein *et al.,* 2022). Characteristics of sustainable agricultural business models include:

- **Environmental stewardship:** Sustainable models promote responsible land and resource management, reducing negative environmental impacts. Practices like crop rotation, organic farming, and reduced chemical pesticide use are common examples of environmentally responsible approaches.
- **Economic viability:** These models aim to ensure the economic well-being of farmers. By minimizing input costs, optimizing production, and seeking fair prices for their products, sustainable farmers strive for profitability while maintaining economic sustainability.
- **Social responsibility:** Sustainable farming is often intertwined with the well-being of local communities. It involves fair labour practices, supporting rural economies, and promoting healthy, locally sourced food.
- **Biodiversity conservation:** Sustainable agricultural business models often prioritize biodiversity conservation. Farmers may implement practices such as agroforestry, the creation of wildlife corridors, and maintaining diverse crop and livestock species.
- **Soil health:** Soil is a crucial resource in agriculture, and sustainable models focus on preserving and enhancing soil health. Techniques like no-till farming, cover cropping, and reduced soil erosion play a significant role in this aspect (Nishad *et al.,* 2011).

3.2 Types of sustainable agricultural business models

There are various types of sustainable agricultural business models, and their suitability can vary depending on factors such as location, climate, available resources, and market demand. Some common types include:

- **Organic farming:** Organic farming avoids synthetic chemicals and genetically modified organisms, focusing on natural inputs, crop rotation, and soil health. Certification is often required to sell products as organic.
- **Permaculture:** Permaculture designs farming systems that mimic natural ecosystems and strive for self-sufficiency. It focuses on maximizing resource efficiency and minimizing waste. This sustainable agricultural approach integrates land, resources, people, and the environment through mutually beneficial synergies, modelled from the natural world. By designing holistic systems that require minimal external inputs, permaculture enables long-term ecological balance and resilience. As shown in Fig. 1, Conceptual permaculture design for sustainable community agriculture in Switzerland, the layout includes elements such as water catchment systems, mulched grassland pathways, diversified cropping zones, and wildlife protection areas, all of which contribute to a regenerative and productive agricultural landscape. This design, developed under the PERMATUR Vision Birchhof project, illustrates how permaculture principles can be translated into practical community-supported agricultural systems that promote biodiversity, optimize spatial planning, and enhance food sovereignty.

Fig. 1: Conceptual permaculture design for sustainable community agriculture in Switzerland (http://www.permatur.org/vision-birchhof-english, 2018); p hoto: Matthias Brück

- **Regenerative agriculture:** Regenerative agriculture goes beyond sustainability by aiming to restore ecosystems and soil health. Practices like no-till farming, cover cropping, and rotational grazing are common regenerative techniques.
    - *Minimize soil disturbance:* Avoid or reduce tillage to protect soil structure, preserve microbial life, and maintain organic matter. This enhances soil health and prevents erosion.
    - *Keep the soil covered:* Maintain a continuous soil cover through cover crops, mulch, or crop residues. This protects the soil from erosion, retains moisture, and suppresses weeds.
    - *Maximize crop diversity:* Practice crop rotation and intercropping to enhance biodiversity above and below the soil. Diverse plant species support a wider range of soil microbes and pest resistance.
    - *Maintain living roots year-round:* Grow cover crops or perennials to ensure living roots are active in the soil throughout the year. This helps sustain soil biology and improves nutrient cycling.
    - *Integrate livestock:* Incorporate managed grazing systems where appropriate. Animals contribute to nutrient cycling, soil fertility, and natural vegetation management.
    - *Context-specific decision-making:* Tailor farming practices to local ecosystems, climates, and community needs. Regenerative agriculture emphasizes observation, adaptation, and continuous learning to restore and enhance the land's productivity sustainably.
- **Community-supported agriculture (CSA):** CSA models involve direct relationships between farmers and consumers. Subscribers buy shares in a farm and receive regular deliveries of produce, creating a strong sense of community support.
- **Agroforestry:** Agroforestry integrates tree cultivation with traditional agriculture, increasing biodiversity, improving soil quality, and enhancing water management.

3.3 Benefits of sustainable farming practices

Sustainable agricultural business models offer a wide range of benefits, not only for the environment but also for farmers, consumers, and society as a whole. Some of the major advantages include:

- **Environmental conservation:** Sustainable farming reduces pollution, protects biodiversity, and minimizes soil erosion, contributing to a healthier planet.
- **Enhanced resilience:** Sustainable practices often make farms more resilient to climate change and extreme weather events.

- **Improved soil health:** These models promote healthier, more fertile soils, leading to higher crop yields and less reliance on synthetic fertilizers.
- **Quality and safety:** Sustainable farming often produces high-quality, safe, and nutritious food products, meeting the demands of conscious consumers.
- **Economic viability:** By minimizing input costs and creating value-added products, sustainable agriculture can enhance the profitability of farming operations.
- **Community and rural development:** Sustainable farming practices can revitalize rural communities, providing jobs and economic opportunities while supporting local food systems.

Sustainable agricultural business models are a crucial aspect of modern farming, promoting responsible and profitable food production. They encompass a range of approaches that prioritize environmental stewardship, economic viability, and social responsibility, ultimately benefiting both farmers and society at large (Klein *et al.*, 2022; Browne *et al.,* 2011).

4. Farm Profitability Analysis

Farm profitability analysis is a critical component of assessing the financial health and sustainability of agricultural operations. It involves evaluating the economic performance of a farm, considering various factors that impact income and expenses (Solimene *et al.,* 2023). To conduct a comprehensive farm profitability analysis, various metrics are used to provide insights into different aspects of the farm's financial performance (Cheng *et al.,* 2022).

4.1 Metrics for assessing farm profitability

4.1.1 Gross margin

Gross margin is the difference between the total revenue generated from farming activities (usually crop sales or livestock sales) and the variable costs associated with producing those products. Variable costs include expenses such as seeds, fertilizers, pesticides, and labour directly related to production.

$$Gross\ margin\ =\ Total\ revenue\ -\ Variable\ costs$$

Implication: Gross margin is a key indicator of the profitability of specific crop or livestock enterprises within the farm. It helps assess the financial performance of individual components of the operation.

Example: Let's say a farm generated $100,000 in revenue from corn sales and incurred $40,000 in variable costs associated with planting and harvesting corn. The gross margin for the corn enterprise would be $60,000 ($100,000 - $40,000).

4.1.2 Net farm income

Net farm income represents the overall profitability of the entire farm after accounting for all farm-related expenses. It considers not only variable costs but also fixed costs like land and equipment maintenance, utilities, and general farm management expenses.

Net farm income = Total revenue - Total costs

Implication: Net farm income provides a holistic view of the farm's financial health, taking into account all costs associated with production. It helps determine the overall profitability and sustainability of the agricultural business.

Example: If a farm generates $500,000 in total revenue from various sources and incurs $400,000 in total costs (both variable and fixed), the net farm income would be $100,000 ($500,000 - $400,000).

4.1.3 Operating profit margin

The operating profit margin is a measure of the farm's ability to generate profit from its core operational activities. It assesses the efficiency of the farm's production and management.

$$Operating\ profit\ margin = \left[\frac{Operating\ profit}{Total\ revenue}\right] \times 100$$

Implication: Operating profit margin provides insight into the farm's operational efficiency and profitability, allowing for comparisons with industry benchmarks.

Example: If a farm's operating profit is $50,000, and its total revenue is $300,000, the operating profit margin would be 16.67% ((50,000 / 300,000) x 100).

These are a few main metrics used in farm profitability analysis to evaluate the financial performance of agricultural businesses. When combined with CBA and return on investment (ROI), they provide a comprehensive picture of how energy efficiency measures impact the financial sustainability of farming operations.

4.2 The role of energy efficiency in profitability

Energy efficiency plays a pivotal role in enhancing farm profitability in many ways:

- **Cost reduction:** Improved energy efficiency leads to lower energy consumption, resulting in reduced operational costs. Farms can cut expenses related to fuel, electricity, and maintenance, directly contributing to higher profit margins. For example, switching to energy-efficient lighting systems or optimizing irrigation practices can significantly lower energy expenses (Kumar *et al.*, 2023).
- **Increased productivity:** Energy-efficient technologies can enhance farm productivity. For instance, precision agriculture tools like GPS-guided tractors and drones can improve crop management, reducing waste and boosting yields. This, in turn, can lead to higher revenue and profitability.
- **Access to incentives and grants:** Many governments and organizations offer incentives, grants, or subsidies for adopting energy-efficient practices in agriculture. By taking advantage of these programs, farms can reduce capital investment costs and enhance their financial viability.

- **Environmental benefits:** Energy-efficient practices align with sustainability goals and reduce a farm's environmental impact. This can be a marketing advantage, appealing to consumers who prioritize eco-friendly products and potentially allowing for premium pricing, further contributing to profitability.

Energy efficiency in agriculture is essential for improving farm profitability by reducing costs, enhancing productivity, and offering access to financial incentives. Efficient energy use contributes to a more sustainable and financially viable agricultural business model, aligning with the broader goals of sustainable agriculture (Baumont de Oliveira *et al.,* 2022).

5. Energy Efficiency Technologies for Agriculture

5.1 Introduction to energy-efficient technologies

Energy-efficient technologies play a pivotal role in transforming the agricultural landscape by enhancing productivity, reducing operational costs, and contributing to environmental sustainability. Various innovative technologies designed to optimize energy consumption in farming:

Modern agriculture heavily relies on energy inputs, which are primarily derived from fossil fuels. These inputs include fuel for tractors, irrigation systems, and transportation, as well as electricity for various equipment and infrastructure. Energy-efficient technologies are essential to mitigate the environmental impact of agriculture and enhance its long-term economic viability (Hamid and Blanchard, 2018).

Energy-efficient technologies encompass a wide array of innovations, ranging from precision farming tools and equipment to renewable energy sources. These technologies help farmers make informed decisions, reduce waste, and utilize resources more sustainably. They can also increase the resilience of farming operations in the face of changing climate conditions and fluctuating energy prices (Cavazza *et al.*, 2023; Brzoska *et al.*, 2022).

5.2 Implementing renewable energy sources

One of the major components of enhancing energy efficiency in agriculture is the integration of renewable energy sources. The shift from fossil fuels to clean, sustainable energy sources not only reduces greenhouse gas emissions but also provides a degree of energy independence and financial stability for farmers (Mathivanan and Jayagopal, 2019). Here, we will discuss the various renewable energy options that can be adopted by agricultural businesses.

- **Solar power:** Solar panels are increasingly becoming a popular choice for agricultural operations. They can be installed on rooftops, in open fields, or on other structures to harness the energy of the sun (as shown in Fig. 2). Solar power not only reduces electricity bills but also offers the possibility of selling excess energy back to the grid (Mishra, 2024). It is particularly advantageous for farms with high electricity demand, such as those with extensive irrigation systems or temperature-controlled storage facilities.

- **Wind energy:** Wind turbines are another renewable energy option for farms, especially in regions with consistent wind patterns. These turbines convert wind energy into electricity and can be used to power farm operations or sold to the grid. Wind energy is a reliable source of power and can be integrated with other renewable energy technologies for a comprehensive approach to sustainability.
- **Biomass energy:** Biomass energy involves using organic materials, such as crop residues, manure, and wood, to produce biogas, biofuels, and heat. This approach is not only environmentally friendly but also allows farmers to make use of waste materials while reducing their reliance on fossil fuels.
- **Small hydropower:** Farms located near streams or rivers can explore small hydropower options. These systems harness the energy of flowing water to generate electricity. Small hydropower is a reliable source of energy and can be used for various applications on the farm.
- **Geothermal energy:** Geothermal systems utilize the natural heat from the Earth to provide heating and cooling for farm buildings. These systems are highly energy-efficient and have a relatively low operational cost, making them a viable option for many agricultural businesses.

Fig. 2: Renewable energy sources (Source: Author's compilation)

Table 1: Benefits and challenges of implementing renewable energy sources

S. No.	Aspect	Benefits	Challenges
1.	Environmental Benefits	Reduces greenhouse gas emissions	Land and habitat disruption
		Mitigates climate change	Resource extraction and pollution
		Lowers air and water pollution	Intermittency and variability
		Preserves natural resources	Energy storage and grid integration
2.	Economic Benefits	Job creation and local economic boost	Initial high installation costs
		Energy independence and security	Energy transition challenges
		Stable energy prices	Competition with fossil fuels
		Investment opportunities	Infrastructure development costs
3.	Social Benefits	Improved public health	Community opposition and NIMBYism
		Energy access for remote areas	Technological and educational gaps
		Energy equity and affordability	Transition impacts on traditional industries
4.	Technological Advancements	Advances in renewable tech	R&D and innovation requirements
		Increased energy efficiency	Manufacturing and supply chain challenges
		Grid modernization and smart tech	Technological and equipment failures
5.	Energy Security	Diversifies energy sources	Dependence on rare materials
		Reduces vulnerability to supply disruptions	Geopolitical issues
		Increases grid resilience	

5.3 Precision agriculture and iot applications

Precision agriculture is an innovative approach that utilizes advanced technologies, including the Internet of Things (IoT), to optimize farming practices and improve energy efficiency. This section discusses how precision agriculture and IoT applications contribute to energy efficiency in farming (Dahan *et al.*, 2010).

Precision agriculture: It involves the use of data-driven technologies and tools to make informed decisions in farming operations. It is characterized by the collection, analysis, and application of real-time data to manage agricultural practices efficiently. Some aspects of precision agriculture include:

- **Sensor technology:** Precision agriculture relies on various sensors such as soil moisture sensors, weather stations, and GPS-equipped machinery. These sensors provide accurate and up-to-date information about the conditions in the field, enabling farmers to make precise decisions.
- **Data analytics:** The collected data is processed and analysed to understand soil conditions, crop health, and other relevant factors. This data-driven approach helps farmers identify areas of improvement and optimize their farming practices.
- **Variable rate technology (VRT):** VRT is a key component of precision agriculture, allowing for precise application of resources like water, fertilizers, and pesticides. Instead of applying these resources uniformly across the entire field, VRT adjusts the application rates based on specific needs, reducing waste and energy consumption.
- **Remote monitoring and control:** IoT applications enable farmers to remotely monitor and control various aspects of their operations, such as irrigation systems, machinery, and environmental conditions. This minimizes the need for physical presence on the farm, saving both time and energy.

5.4 Efficient irrigation and water management

Efficient water management is critical for both reducing energy consumption and ensuring sustainable agriculture.

- **Drip irrigation:**

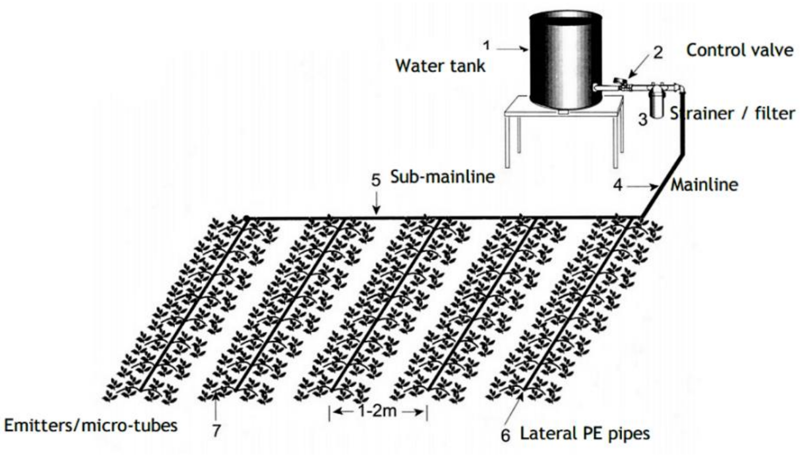

Fig. 3: Schematic diagram of a typical drip irrigation system layout. (Source: https://sswm.info/ar/sswm-solutions-bop-markets/affordable-wash-services-and-products/affordable-technologies-and/drip-irrigation)

In modern sustainable agriculture, drip irrigation has emerged as a vital technique to optimize water use efficiency. Drip irrigation systems are designed to deliver water directly to the root zone of plants through a network of components including water tanks, control valves, filters, sub-mainlines, lateral pipes, and emitters. As shown in Fig. 3, this system ensures that water is distributed precisely where it is needed, reducing losses due to evaporation and surface runoff. The method promotes substantial water and energy conservation, especially in regions with limited water resources. Furthermore, by maintaining optimal soil moisture levels, drip irrigation supports healthier plant growth and improves crop yields, contributing to both food security and resource sustainability.

- **Soil moisture sensors:** Soil moisture sensors are integral to optimizing irrigation. These devices monitor soil moisture levels and provide data that helps farmers determine when and how much water to apply. By preventing over-irrigation, which can be energy-intensive, farmers conserve water and reduce energy consumption.
- **Weather-based irrigation controllers:** Modern irrigation systems can be equipped with weather-based controllers that adjust irrigation schedules based on real-time weather conditions. These controllers optimize water usage, avoiding unnecessary irrigation during periods of rainfall or high humidity, which can save energy and resources.

5.5 Machinery and equipment upgrades

Upgrading farm machinery and equipment is an effective way to enhance energy efficiency in agriculture. This section discusses the various technological advancements and practices that enable farmers to reduce energy consumption in their operations.

- **Energy-efficient tractors and implements:** Modern tractors and farm implements are designed to be more energy-efficient, often using advanced engines and transmission systems. These upgrades result in reduced fuel consumption and lower emissions. Additionally, some machinery is equipped with GPS and auto-steering systems that optimize field operations, further saving time and energy (Mishra, 2024).
- **Electric and solar-powered machinery:** The adoption of electric and solar-powered machinery is on the rise, particularly for tasks like irrigation, harvesting, and transportation. Electric tractors and implements can significantly reduce the use of fossil fuels, while solar-powered equipment can harness renewable energy sources to operate efficiently.
- **Maintenance and retrofitting:** Regular maintenance and retrofitting of existing machinery and equipment can improve their energy efficiency. This includes upgrading engines, optimizing fuel consumption, and enhancing overall performance.

Energy-efficient technologies for agriculture offer numerous opportunities for farmers to enhance their profitability while minimizing their environmental footprint (Nandal and Dahiya, 2023). The adoption of renewable energy sources, precision agriculture techniques, efficient irrigation and water management systems, and machinery upgrades can collectively contribute to sustainable and economically viable agricultural business models (Koohafkan *et al.*, 2012). By embracing these technologies, farmers can meet the growing demand for environmentally responsible farming practices while securing their long-term financial success (Jawad *et al.*, 2017; Pan *et al.*, 2018).

6. Financial Analysis of Energy Efficiency Investments

6.1 Cost-benefit analysis

Cost-benefit analysis (CBA) is a crucial financial tool used to evaluate the feasibility and desirability of energy efficiency investments in agriculture. It is a systematic process for comparing the costs of an investment or project with its expected benefits, expressed in monetary terms. CBA is an essential component of assessing the potential return on investment for energy-efficient practices on the farm (Ilyas *et al.*, 2020).

CBA is a structured method for assessing the economic feasibility of a project or investment by comparing the total costs associated with it to the total benefits it is expected to generate. The goal is to determine whether the benefits outweigh the costs and whether the investment is financially sound.

Formula for CBA: Net benefits = Total benefits - Total costs

Where:

- Total benefits: The sum of all the positive monetary outcomes or savings resulting from the investment.
- Total costs: The sum of all the expenses incurred in implementing and operating the energy efficiency measures.

Implications of CBA:

The implications of conducting a CBA in the context of energy efficiency investments in agriculture are profound:

- Decision-making: CBA provides decision-makers with a clear quantitative assessment of whether an investment in energy efficiency is economically justified. It helps stakeholders make informed choices and allocate resources efficiently.
- Project prioritization: By comparing the net benefits of different energy efficiency projects, CBA helps prioritize investments that provide the greatest return on investment. This ensures that limited resources are allocated to projects that deliver the most significant economic impact.
- Risk mitigation: CBA allows for the consideration of potential risks and uncertainties associated with an investment, helping to identify areas where risk mitigation measures may be necessary.
- Policy and regulation: Governments and regulatory bodies often use CBA to assess the potential economic impacts of energy efficiency policies and regulations in the

agricultural sector. This analysis informs the development and implementation of policies that promote sustainable practices.

Example of CBA: A farmer is considering investing $10,000 in energy-efficient irrigation equipment. The expected annual energy cost savings from using this equipment is $2,000. The equipment has an estimated useful life of 5 years.

Total benefits:

Annual savings = $2,000

Total savings over 5 years = $2,000 × 5 = $10,000

Total costs:

Initial investment = $10,000

Net benefits = Total benefits - Total costs

Net benefits = $10,000 - $10,000 = $0

In this example, the CBA indicates that the investment in energy-efficient irrigation equipment does not yield a positive net benefit over the equipment's useful life. Therefore, based on this analysis, the farmer may choose not to proceed with the investment.

It's important to note that CBA should take into account the time value of money and consider the impacts of the investment over its entire lifespan. Additionally, non-monetary benefits, such as environmental benefits or increased farm resilience, should be considered to provide a more comprehensive evaluation.

6.2 Return On Investment (ROI)

Return on Investment, commonly referred to as ROI, is a financial metric used to evaluate the profitability and efficiency of an investment. In the context of agriculture, ROI helps farmers determine whether their investments in energy efficiency measures are economically viable. ROI is usually expressed as a percentage and indicates the return generated relative to the initial investment.

$$ROI\ (\%) = \left[\frac{Net\ profit\ from\ investment}{Initial\ investment}\right] \times 100$$

Where:

- Net Profit from Investment is the total profit earned from the investment, considering costs and revenues.
- Initial Investment is the amount of money invested in energy efficiency measures.

Implications of ROI in Agriculture:

- Investment decision-making: Farmers and agricultural businesses use ROI to assess whether it is financially worthwhile to invest in energy-efficient technologies and practices. It helps them prioritize investments by comparing the potential returns from various options.

- Resource allocation: ROI analysis allows farmers to allocate their resources effectively. It helps them identify which energy efficiency projects are likely to deliver the best financial returns, ensuring that funds are directed to projects that offer the most significant benefits.
- Risk assessment: ROI is also a useful tool for evaluating the level of risk associated with an investment. By comparing the expected ROI to the risk tolerance of the farm, decision-makers can make informed choices regarding energy efficiency projects.
- Continuous improvement: By regularly analysing ROI, farmers can monitor the performance of their energy efficiency investments. This data-driven approach enables them to make adjustments and improvements to maximize returns over time.

Example: A farmer invests $10,000 in upgrading their irrigation system to a more energy-efficient model. This investment results in annual energy cost savings of $2,000. Additionally, the improved system leads to increased crop yields, resulting in an extra $3,000 in annual revenue.

$$ROI\ (\%) = \left[\frac{(Annual\ Savings\ +\ Annual\ Additional\ Revenue)}{Initial\ Investment}\right] \times 100$$

$$ROI = \left[\frac{(\$2{,}000\ + \$3{,}000)}{\$10{,}000}\right] \times 100$$

$$ROI = \left[\frac{\$5{,}000}{\$10{,}000}\right] \times 100$$

ROI = 50%

In this scenario, the ROI for the investment in the energy-efficient irrigation system is 50%. This means that for every dollar invested, the farmer can expect to earn an additional $0.50 in profit. A positive ROI indicates that the investment is financially sound and is likely to contribute to the farm's profitability (Mishra, 2025).

Ultimately, ROI analysis is a valuable tool for farmers to make informed decisions about energy efficiency investments, ensuring that they achieve both economic and environmental sustainability in their agricultural operations.

6.3 Government incentives and subsidies

Government incentives and subsidies play a pivotal role in encouraging farmers to invest in energy-efficient practices and technologies. These incentives are designed to ease the financial burden associated with implementing energy-efficient measures, making it more attractive for agricultural businesses to adopt sustainable practices. Government incentives and subsidies are financial support mechanisms provided by local, state, or federal governments to stimulate the adoption of energy-efficient practices in the agricultural sector. These incentives can take various forms, including tax credits, grants, rebates, and low-interest loans. Objective of these programs is to reduce the overall energy consumption of the agricultural sector, lower greenhouse gas emissions, and enhance the sustainability of farming operations (Chel and Kaushik, 2011).

Advantages of government support: Government incentives and subsidies offer many advantages for farmers looking to invest in energy efficiency:

- **Reduced initial investment costs:** Government support can significantly offset the upfront costs of energy-efficient technologies and practices. This makes it more feasible for farmers to implement these measures, as they may have otherwise been financially burdensome.
- **Lower operational costs:** Energy-efficient technologies typically result in reduced energy consumption and, consequently, lower operational costs. This translates into higher profitability for farmers in the long run.
- **Environmental benefits:** Many government programs focus on reducing the environmental impact of farming operations. By encouraging energy efficiency, they contribute to a reduction in greenhouse gas emissions, water conservation, and other eco-friendly practices.

Types of government incentives and subsidies: Government support programs for energy efficiency in agriculture can encompass a variety of initiatives, including:

1. **Tax credits:** Governments may offer tax credits for the purchase and installation of energy-efficient equipment, such as solar panels, energy-efficient lighting, or irrigation systems.
2. **Grants:** Grant programs provide direct financial assistance to farmers for energy efficiency projects. These grants may cover a portion or the entirety of the project costs.
3. **Rebates:** Rebate programs offer financial incentives to farmers who replace old, inefficient equipment with more energy-efficient alternatives.
4. **Low-interest loans:** Governments may partner with financial institutions to offer low-interest loans to farmers for energy efficiency projects. These loans typically have favourable terms to make them more accessible to agricultural businesses.

Table 2: Government incentives and subsidies for farm profitability in India

S. No.	Incentive/Subsidy Type	Description
1.	Minimum Support Price (MSP)	A guaranteed price that the government sets for various crops to ensure farmers receive a minimum income for their produce.
2.	Pradhan Mantri Kisan Samman Nidhi (PM-KISAN)	A direct income support scheme that provides financial assistance to small and marginal farmers in the form of income transfer (Mishra and Mishra, 2024).

3.	Rashtriya Krishi Vikas Yojana (RKVY)	A centrally sponsored scheme aimed at providing financial support to state governments to promote agricultural development and ensure food security.
4.	Soil Health Card Scheme	A program that provides farmers with soil health cards, offering information about the health of their soil and recommendations for appropriate fertilizer use, thereby increasing crop yields (Mishra, 2025).
5.	National Mission on Sustainable Agriculture (NMSA)	Focused on promoting sustainable agricultural practices, including organic farming, soil health management, and efficient water use.
6.	Pradhan Mantri Fasal Bima Yojana (PMFBY)	A crop insurance scheme that provides financial protection to farmers in case of crop losses due to natural calamities, pests, or diseases.
7.	Subsidies on Agricultural Machinery	Subsidies on the purchase of various agricultural machinery and equipment to improve farm productivity and efficiency.
8.	Interest Subvention Scheme for Short-term Crop Loans	Provides interest rate subsidies to farmers on short-term crop loans, making credit more affordable and accessible.
9.	National Agriculture Market (eNAM)	An electronic trading platform that connects agricultural produce markets, enabling farmers to sell their produce online, helping them get better prices.
10.	Mission for Integrated Development of Horticulture (MIDH)	Promotes the development of horticulture, including fruits, vegetables, and flowers, by providing financial support for various activities like orchard establishment and post-harvest management.

These are just a few examples of the various incentives and subsidies that the Indian government provides to promote farm profitability and support the agricultural sector (Mishra, 2025).

Maximizing the benefits of government support: To make the most of government incentives and subsidies for energy efficiency investments in agriculture, farmers should consider the following:

1. **Stay informed:** Keep abreast of the latest government programs and opportunities. Government support programs may change over time, so it's essential to stay informed about new offerings.

2. **Compliance:** Ensure that your energy efficiency project complies with the requirements of the specific government program. Non-compliance can lead to ineligibility for incentives.
3. **Plan carefully:** Develop a comprehensive plan for your energy efficiency project to maximize the benefits of government support. This includes estimating project costs, anticipated energy savings, and the potential return on investment.
4. **Seek expert assistance:** Consult with agricultural extension services, energy auditors, or other experts to identify the best energy-efficient technologies and practices for your specific farming operation. They can also help with the application process for government incentives.

Government incentives and subsidies are essential components of the financial analysis of energy efficiency investments in agriculture. They not only help reduce the financial barriers to adopting sustainable practices but also contribute to the long-term profitability and sustainability of farming operations (Mishra *et al.,* 2011). Farmers should proactively explore available government support options and ensure they meet the program requirements to harness the full range of benefits (Long *et al.,* 2018).

7. Sustainable Agricultural Practices

Sustainable agricultural practices are fundamental to achieving farm profitability through energy efficiency. They not only help in reducing the environmental impact of farming but also contribute to the long-term viability of agricultural businesses.

7.1 Organic farming and soil health

Organic farming is an essential component of sustainable agriculture, promoting healthy soil ecosystems. In this sub-section, we explore the relationship between organic farming and soil health. Organic farming practices, such as the use of organic fertilizers and crop rotation, promote the enrichment of soil organic matter and microbial diversity (Mohseni *et al.,* 2018). This, in turn, improves soil structure, water retention, and nutrient cycling. Healthy soils are more resilient to environmental stressors, leading to increased crop productivity and reduced energy-intensive inputs.

7.2 Crop rotation and pest management

Crop rotation is a practice that involves alternating crops in a specific sequence in the same field over several seasons. It plays a crucial role in sustainable agriculture by improving soil health and reducing the need for synthetic pesticides (Table 3) (Riccaboni *et al.,* 2021). By preventing soil degradation and reducing the reliance on energy-intensive chemical inputs, crop rotation contributes to both economic and environmental sustainability in agriculture (Lieder and Rashid, 2016).

(ISBN: 978-93-48620-17-0)

Table 3: Benefits of crop rotation

S. No.	Benefit of crop rotation	Description
1.	Pest and disease management	Crop rotation helps break the life cycles of pests and pathogens, reducing the risk of infestations and diseases.
2.	Nutrient management	Different crops have varying nutrient requirements, allowing for more efficient use of soil nutrients and reducing the need for synthetic fertilizers.
3.	Soil health improvement	Crop rotation can enhance soil structure, prevent soil erosion, and promote beneficial microorganisms, improving overall soil health.
4.	Weed control	Crop rotation disrupts weed growth patterns and reduces the prevalence of specific weed species, minimizing the need for herbicides.
5.	Increased yields	By reducing the depletion of specific nutrients and mitigating pests and diseases, crop rotation often leads to increased crop yields.
6.	Sustainable agriculture	It promotes a more sustainable and environmentally friendly agricultural system by reducing the reliance on chemical inputs.
7.	Risk management	Diversifying crops in a rotation helps farmers hedge against unpredictable weather conditions and market fluctuations.
8.	Enhanced crop quality	Crop rotation can result in better crop quality, taste, and nutritional value, improving marketability.

Effective pest management is another aspect of sustainable agriculture discussed in this sub-section. Integrated pest management (IPM) strategies, which focus on biological control and reduced chemical pesticide usage, help maintain ecosystem balance while reducing energy-intensive practices. These approaches not only enhance the sustainability of farming but also reduce operational costs, improving farm profitability (Musa and Basir, 2021).

7.3 Biodiversity and ecosystem services

Biodiversity and ecosystem services are integral to the sustainability of agricultural systems. In this sub-section, we explore the importance of preserving biodiversity within and around farms and how it contributes to energy-efficient and profitable farming (Clairand *et al.*, 2020). Biodiversity supports natural pest control, enhances soil health, and promotes pollination, reducing the need for energy-intensive interventions. Moreover, maintaining hedgerows, riparian zones, and other natural habitats in and around farms provides ecosystem services that benefit agriculture, such as water purification, flood control, and climate regulation.

These practices not only align with environmental goals but also provide economic incentives for farmers, making them a win-win solution for modern agriculture.

Conclusion:

Achieving farm profitability through energy efficiency is essential in today's agricultural landscape. This analysis underscores the importance of understanding energy consumption patterns and the various factors influencing their use. Sustainable agricultural business models provide a viable path forward, offering ecological, economic, and social benefits. Energy efficiency is central to improving profitability, supported by technologies such as renewable energy, precision agriculture, efficient irrigation, and modernized equipment. Financial assessments like cost-benefit analysis and return on investment are crucial for evaluating energy-related investments. Government incentives and subsidies further encourage the adoption of energy-efficient practices. Sustainable farming methods—such as organic agriculture, crop rotation, and biodiversity conservation—support both profitability and environmental resilience. Growing consumer demand for sustainable products creates new market opportunities, reinforced by certification and labelling systems. Policy and regulatory frameworks, including government initiatives and environmental regulations, play a key role in guiding sustainable agricultural practices. Despite challenges—technological, economic, and behavioural—strategic approaches, training, and innovation can help overcome these barriers. Farm profitability through energy efficiency is achievable with a strong commitment to sustainability, supportive policies, and the adoption of advanced technologies. This transition benefits not only farmers but also contributes to a more resilient and sustainable agricultural future.

References:

1. Baumont de Oliveira, F. J., Ferson, S., Dyer, R. A., Thomas, J. M., Myers, P. D., & Gray, N. G. (2022). How high is high enough? Assessing financial risk for vertical farms using imprecise probability. *Sustainability*, *14*(9), 5676, https://doi.org/10.3390/su14095676.
2. Björklund, J. C., & Ulvenblad, P. (2016). Sustainable business models in Swedish agri-food production-Challenges and barriers.
3. Browne, N. A., Eckard, R. J., Behrendt, R., & Kingwell, R. S. (2011). A comparative analysis of on-farm greenhouse gas emissions from agricultural enterprises in south eastern Australia. *Animal Feed Science and Technology*, *166*, 641-652, https://doi.org/10.1016/j.anifeedsci.2011.04.045.
4. Brzóska, J., Knop, L., Odlanicka-Poczobutt, M., & Zuzek, D. K. (2022). Antecedents of creating business models in the field of renewable energy based on the concept of the new age of innovation. *Energies*, *15*(15), 5511, https://doi.org/10.3390/en15155511.
5. Cavazza, A., Dal Mas, F., Campra, M., & Brescia, V. (2023). Artificial intelligence and new business models in agriculture: the "ZERO" case study. *Management Decision*, https://doi.org/10.1108/MD-06-2023-0980.

6. Cavazza, A., Dal Mas, F., Paoloni, P., & Manzo, M. (2023). Artificial intelligence and new business models in agriculture: a structured literature review and future research agenda. *British Food Journal*, *125*(13), 436-461, https://doi.org/10.1108/BFJ-02-2023-0132.
7. Chel, A., & Kaushik, G. (2011). Renewable energy for sustainable agriculture. *Agronomy for sustainable development*, *31*, 91-118, https://doi.org/10.1051/agro/2010029.
8. Cheng, J., Wang, Q., Li, D., & Yu, J. (2022). Comparative analysis of environmental and economic performance of agricultural cooperatives and smallholder farmers for apple production in China. *Agriculture*, *12*(8), 1281, https://doi.org/10.3390/agriculture12081281.
9. Clairand, J. M., Briceno-Leon, M., Escriva-Escriva, G., & Pantaleo, A. M. (2020). Review of energy efficiency technologies in the food industry: trends, barriers, and opportunities. *IEEE Access*, *8*, 48015-48029, https://doi.org/10.1109/ACCESS.2020.2979077.
10. Dahan, N. M., Doh, J. P., Oetzel, J., & Yaziji, M. (2010). Corporate-NGO collaboration: Co-creating new business models for developing markets. *Long range planning*, *43*(2-3), 326-342, https://doi.org/10.1016/j.lrp.2009.11.003.
11. De Keyser, E., & Mathijs, E. (2023). A typology of sustainable circular business models with applications in the bioeconomy. *Frontiers in Sustainable Food Systems*, *6*, 1028877, https://doi.org/10.3389/fsufs.2022.1028877.
12. *Drip irrigation*. (n.d.). https://sswm.info/ar/sswm-solutions-bop-markets/affordable-wash-services-and-products/affordable-technologies-and/drip-irrigation
13. Engler, N., & Krarti, M. (2021). Review of energy efficiency in controlled environment agriculture. *Renewable and Sustainable Energy Reviews*, *141*, 110786, DOI: 10.1016/j.rser.2021.110786.
14. Hamid, R. G., & Blanchard, R. E. (2018). An assessment of biogas as a domestic energy source in rural Kenya: Developing a sustainable business model. *Renewable Energy*, *121*, 368-376, DOI: 10.1016/j.renene.2018.01.032.
15. Ilyas, H. M. A., Safa, M., Bailey, A., Rauf, S., & Khan, A. (2020). Energy efficiency outlook of New Zealand dairy farming systems: An application of data envelopment analysis (DEA) approach. *Energies*, *13*(1), 251, DOI: 10.3390/en13010251.
16. Jawad, H. M., Nordin, R., Gharghan, S. K., Jawad, A. M., & Ismail, M. (2017). Energy-efficient wireless sensor networks for precision agriculture: A review. *Sensors*, *17*(8), 1781, DOI: 10.3390/s17081781.

17. Klein, O., Nier, S., & Tamásy, C. (2022). Circular agri-food economies: business models and practices in the potato industry. *Sustainability Science*, *17*(6), 2237-2252, DOI: 10.1007/s11625-022-01106-1.
18. Koohafkan, P., Altieri, M. A., & Gimenez, E. H. (2012). Green agriculture: foundations for biodiverse, resilient and productive agricultural systems. *International Journal of Agricultural Sustainability*, *10*(1), 61-75, DOI: 10.1080/14735903.2011.610206.
19. Kumar, N., Kushwaha, R. R., Meena, N. R., Mishra, H., & Yadav, A. P. S. (2023). A study on costs and returns of paddy cultivation in Ambedkar Nagar district of Uttar Pradesh. *International Journal of Statistics and Applied Mathematics, SP*, *8*(3), 107-111.
20. Kyriakarakos, G., Balafoutis, A. T., & Bochtis, D. (2020). Proposing a paradigm shift in rural electrification investments in Sub-Saharan Africa through Agriculture. *Sustainability*, *12*(8), 3096, DOI: 10.3390/su12083096.
21. Lewandowski, M. (2016). Designing the business models for circular economy—Towards the conceptual framework. *Sustainability, 8*(1), 43, DOI: 10.3390/su8010043.
22. Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *Journal of cleaner production*, *115*, 36-51, DOI: 10.1016/j.jclepro.2015.12.042.
23. Long, T. B., Looijen, A., & Blok, V. (2018). Critical success factors for the transition to business models for sustainability in the food and beverage industry in the Netherlands. *Journal of cleaner production*, *175*, 82-95, DOI: 10.1016/j.jclepro.2017.11.067.
24. Lutsiak, V., Hutsol, T., Kovalenko, N., Kwaśniewski, D., Kowalczyk, Z., Belei, S., & Marusei, T. (2021). Enterprise Activity Modeling in Walnut Sector in Ukraine. *Sustainability*, *13*(23), 13027, DOI: 10.3390/su132313027.
25. Madau, F. A., Arru, B., Furesi, R., & Pulina, P. (2020). Insect farming for feed and food production from a circular business model perspective. *Sustainability*, *12*(13), 5418, DOI: 10.3390/su12135418.
26. Mathivanan, S., & Jayagopal, P. (2019). A big data virtualization role in agriculture: a comprehensive review. *Walailak Journal of Science and Technology (WJST)*, *16*(2), 55-70, DOI: 10.48048/wjst.2019.3620.
27. Maturo, A., Petrucci, A., Forzano, C., Giuzio, G. F., Buonomano, A., & Athienitis, A. (2021). Design and environmental sustainability assessment of energy-independent communities: The case study of a livestock farm in the North of Italy. *Energy Reports*, *7*, 8091-8107, DOI: 10.1016/j.egyr.2021.05.080.
28. Mishra, H. (2024). Nanobiostimulants and Precision Agriculture: A Data-Driven Approach to Farming and Market Dynamics. In *Nanobiostimulants: Emerging Strategies for*

Agricultural Sustainability (pp. 365-398). Cham: Springer Nature Switzerland, DOI: 10.1007/978-3-031-68138-7_16.

29. Mishra, H. (2024). The Role of Ethnoeconomics in Promoting Sustainable Consumption and Production Patterns: A Pathway to Environmental Protection and Economic Prosperity. *Sustainable Development*. In *Seen Through the Lenses of Ethnoeconomics and the Circular Economy* (pp. 91-123). Cham: Springer Nature Switzerland, DOI: 10.1007/978-3-031-72676-7_6.
30. Mishra, H. (2025). Artificial Intelligence, Machine Learning and IoT Integration in Agriculture: A Review. *Journal of Science Research International, 11*(1), 110-127.
31. Mishra, H. (2025). Environmental Degradation and Impacts on Agricultural Production: A Challenge to Urban Sustainability. In *Sustainable Urban Environment and Waste Management: Theory and Practice* (pp. 53-92). Singapore: Springer Nature Singapore, DOI: 10.1007/978-981-96-1140-9_3.
32. Mishra, H. (2025). Strategies for Achieving Free Trade and Removing Barriers to the Movement of Goods and Services Within Integrated Economies. In *Economic Integration Strategies, Challenges and Global Implications* (pp. 91-113). Nova Science Publishers, Inc.
33. Mishra, H., & Mishra, D. (2024). AI for Data-Driven Decision-Making in Smart Agriculture: From Field to Farm Management. In *Artificial Intelligence Techniques in Smart Agriculture* (pp. 173-193). Singapore: Springer Nature Singapore, DOI: 10.1007/978-981-97-5878-4_11.
34. Mishra, H., & Mishra, D. (2024). Economic evaluation of UAV-based soil sampling approaches. In *Applications of Computer Vision and Drone Technology in Agriculture 4.0* (pp. 271-291). Singapore: Springer Nature Singapore, DOI: 10.1007/978-981-99-8684-2_15.
35. Mishra, H., & Mishra, D. (2024). Sustainable Smart Agriculture to Ensure Zero Hunger. In *Sustainable Development Goals* (pp. 16-37). CRC Press, DOI: 10.1201/9781003468257-2.
36. Mishra, H., & Mishra, D. (Eds.). (2023). Artificial Intelligence and Machine Learning in Agriculture: Transforming Farming Systems. In Research Trends in Agriculture Science (Volume I), 1-16. Bhumi Publishing.
37. Mishra, H., Tiwari, A. K., & Nishad, D. C. (2011). Economic viability of sustainable agriculture practices in modern farming. *Advances in Agriculture Sciences Volume II*, *24*(4), 105.
38. Mohseni, P., Borghei, A. M., & Khanali, M. (2018). Coupled life cycle assessment and data envelopment analysis for mitigation of environmental impacts and enhancement of

energy efficiency in grape production. *Journal of cleaner production*, *197*, 937-947, DOI: 10.1016/j.jclepro.2018.06.243.

39. Mukoro, V., Sharmina, M., & Gallego-Schmid, A. (2022). A review of business models for access to affordable and clean energy in Africa: Do they deliver social, economic, and environmental value? *Energy Research & Social Science*, *88*, 102530, DOI: 10.1016/j.erss.2022.102530.
40. Musa, S. F. P. D., & Basir, K. H. (2021). Smart farming: towards a sustainable agri-food system. *British Food Journal*, *123*(9), 3085-3099, DOI: 10.1108/BFJ-03-2021-0325.
41. Mushi, G. E., Di Marzo Serugendo, G., & Burgi, P. Y. (2022). Digital technology and services for sustainable agriculture in Tanzania: A literature review. *Sustainability*, *14*(4), 2415, DOI: 10.3390/su14042415.
42. Nandal, V., & Dahiya, S. (2023). A comprehensive review of energy efficient wireless communication and routing protocols in smart agriculture. *Int. J. Sensor Networks*, *43*(2), 99, DOI: 10.1504/IJSNET.2023.134308.
43. Nishad, D. C., Mishra, H., Tiwari, A. K., & Mishra, D. (2011). Post-harvest Management: Enhancing food security and sustainability. *Advances in Agriculture Sciences Volume II*, *24*(4), 136.
44. Nishad, D. C., Mishra, H., Tiwari, A. K., & Pandey, A. (Eds.) (2023). Towards Sustainable Agriculture: Mitigating the Adverse Effects of Stubble Burning in India. *Research Trends in Environmental Science* (Volume I, pp: 42-48). Bhumi Publishing.
45. Pan, S. Y., Gao, M., Kim, H., Shah, K. J., Pei, S. L., & Chiang, P. C. (2018). Advances and challenges in sustainable tourism toward a green economy. *Science of the total environment*, *635*, 452-469, DOI: 10.1016/j.scitotenv.2018.04.134.
46. Reis, I. F., Gonçalves, I., Lopes, M. A., & Antunes, C. H. (2021). Business models for energy communities: A review of key issues and trends. *Renewable and Sustainable Energy Reviews*, *144*, 111013, DOI: 10.1016/j.rser.2021.111013.
47. Riccaboni, A., Neri, E., Trovarelli, F., & Pulselli, R. M. (2021). Sustainability-oriented research and innovation in 'farm to fork'value chains. *Current Opinion in Food Science*, *42*, 102-112, DOI: 10.1016/j.cofs.2021.04.006.
48. Richter, M. (2013). Business model innovation for sustainable energy: German utilities and renewable energy. *Energy Policy*, *62*, 1226-1237, DOI: 10.1016/j.enpol.2013.05.038.
49. Solimene, S., Coluccia, D., & Bernardo, A. (2023). Environmental impact of different business models: An LCA study of fresh tomato production in Italy. *Sustainability*, *15*(13), 10365, DOI: 10.3390/su151310365.

50. Tiwari, A. K., Mishra, H., & Nishad, D. C. (2011). Market dynamics and consumer perceptions of organic produce in contemporary agriculture. *Advances in Agriculture Sciences Volume II*, *24*(4), 120.
51. Tiwari, A. K., Mishra, H., Nishad, D. C., & Pandey, A. (Eds.). (2023). Sustainable Water Management in Agriculture: Irrigation Techniques and Water Conservation (pp. 53-68). In Research Trends in Agriculture Science (Volume II). Bhumi Publishing.
52. Ulvenblad, P. O. (2021). Development of Sustainable Business Models for Innovation in the Swedish Agri-sector: Resource-Effective Producer or Stewardship-Based Entrepreneur?. *The Innovation Revolution in Agriculture: A Roadmap to Value Creation*, 117-145.
53. Ulvenblad, P. O., Ulvenblad, P., & Tell, J. (2019). An overview of sustainable business models for innovation in Swedish agri-food production. *Journal of Integrative Environmental Sciences*, *16*(1), 1-22, DOI: 10.1080/1943815X.2018.1554590.
54. Upward, A., & Jones, P. (2016). An ontology for strongly sustainable business models: Defining an enterprise framework compatible with natural and social science. *Organization & Environment*, *29*(1), 97-123, DOI: 10.1177/1086026615592933.
55. Van Der Wal, S. (2008). Sustainability issues in the tea sector: A comparative analysis of six leading producing countries. *Stichting Onderzoek Multinationale Ondernemingen, June*.
56. *Vision Birchhof (in english) — PERMATUR.* (n.d.). PERMATUR. https://www.permatur.org/vision-birchhof-english

ETHNOBOTANICAL EXPLORATION AND PHYTOCHEMICAL SCREENING OF *ACHYRANTHES ASPERA* L.: A CASE STUDY FROM KALAHANDI DISTRICT, ODISHA, INDIA

Somyashree Sahu[1], Nihar Ranjan Nayak[2],

Ghanashyam Behera[3] and Alok Ranjan Sahu*[1]

[1]Department of Botany,

Vikash Degree College, Barahaguda, Canal Chowk, Bargarh, Odisha

[2]Department of Botany,

Guru Ghasidas Vishwavidyalaya (A Central University,) Bilaspur, (C. G.)

[3]Department of Botany,

Maa Manikeshwari University, Manikya Vihar, Bhawanipatna, Odisha

*Corresponding author E-mail: alok.btgene@gmail.com

Abstract:

Present study deals with the ethnobotanical exploration of *Achyranthes aspera* commonly known as aphamarga in odia (family: Amaranthaceae) by the native of Kalahandi district. Further, collecting the plant parts and phytochemical screening were carried out by using various extracts prepared by shaking and boiling method and documented. Steroid was found to be absent in all extracts prepared by using solvents (methanol, ethanol & water) by both methods. Tannin is present in the shoot and root of several extracts isolated by different solvent using shaking as well as boiling method. Terpenoids are absent in all parts of the plant. Alkaloid is present in methanolic, ethanolic and water extracts of both methods. Phenol was absent in all extract made by shaking method and present in extract using methanol, ethanol and water as solvent and using boiling method. Leaf and inflorescence contain flavanoid. Saponin was present in root and stem parts by shaking method whereas it was found in leaf and inflorescence extract by boiling method. Coumarin was found in all the three extracts. The phytochemical studies with solvent i.e. methanol, ethanol and water extracts of various parts of the plant by shaking and boiling method showed that they possess secondary metabolites. Medicinal plants have received great attention as potential antiperoxidative agents. Plant products are also known for their protective effects by scavenging free radicals and modulating carcinogen detoxification and antioxidant defence systems. The qualitative study of *A. aspera* reveals the presence of a number of secondary metabolites.

Keywords: *Achyranthes aspera*, Amaranthaceae, Phytochemical Screening, Kalahandi District.

Introduction:

Achyranthes aspera commonly known as 'chirchira', aphamarga in odia belongs to the family Amaranthaceae. From ancient times the tribal and rural people used this herb in a variety of disorders. Chirchira has occupied a pivotal position in Indian culture and folk medicine. It has been used in almost all the traditional systems of medicine viz., Ayurveda, Unani and Sidha. According to Ayurveda, it is bitter, pungent, laxative, stomachic, carminative and useful for the treatment of vomiting, bronchitis, heart disease, piles, itching, abdominal pain, ascites, dysentery, blood disease etc. (Dwivedi, 2003). Although it has many medicinal properties, it is particularly used as spermicidal (Paul *et al.*, 2006), antipyretic (Sutar *et al.*, 2008), abortifacient activity (Shibeshi *et al.*, 2006), antibacterial (Khan *et al.*, 2010; Prasad *et al.*, 2009; Sharma *et al.*, 2006), wound healing (Edwin *et al.*, 2008), anti parasitic (Zahir *et al.*, 2009), anti-helmintic activities (Bharathi *et al.*, 2013), etc. Sahu *et al.* (2010) reported that the leaves and roots of *Achyranthes aspera* L. used for the treatment of scorpion Bite, dental problem and dysentery by the native of Bargarh district, Odisha. Sahu *et al.* (2013) reported that the leaves of *A. aspera* were used for the treatment of scorpion bite, blood dysentery, and dental problems by the native of Sohela Block, Western Odisha. Sahu and Sahu (2017) reported that small branches of *A. aspera* are cut into small pieces and used as toothbrushes; mixture of the twig is also used as a wash for tooth pain. The dried root powder is used as toothpaste and it is used to treat gum disorders. Further Soak cotton in the extract of 3-4 leaves and apply it on the aching tooth. It also helps in filling and healing up of old time cavities by the natives of Bargarh District, Western Odisha. Sahu *et al.* (2020) stems of aphamarga are used as toothbrushes; a mixture of twigs is also used as a wash to get relief from tooth pain by the tribal community of Kalahandi district. Sahu *et al.* (2020) reported that leaves and roots of *A. aspera* are used for the treatment of scorpion bite, dental problem; dysentery, brushing teeth cures pyorrhea and toothache by the tribal of Kalahandi District, Odisha. Sahu *et al.* (2021) reported that the Sahara tribal groups of Kangaon village of Bargarh district in western Odisha used the leaves, roots and stems of *A. aspera* for the treatment of Typhoid, toothbrush and tongue cleaner. Sahu *et al.* (2021) reported that the root paste of *A. aspera* var. *indica* L. is applied externally on abdomen for quick delivery by the natives of Bargarh District, Western Odisha. Mishra *et al.* (2022) reported the use of the paste from the whole plant of *A. aspera* is made and applied externally in case of ringworm by the Native of Bargarh District, Odisha, India. Sahu and Mishra (2022) reported that the Root powder of *A. aspera* is added to cow milk and taken to relieve the menstrual disorder by the native of Bargarh district, Western Odisha, India. Sahu and Sahu (2023) reported that inhalation of dried leaves of *A. aspera* smoke through a chillum (mud pipe utilized for smoking) gives moment alleviation from asthmatic wheezing. The plant separates blended in with equivalent sum honey is coordinated to give youngsters two times every day in a void stomach to control bronchial hack. In constant windedness, 5 gm root powder blended in with 5-7 dark peppers added with a glass of tepid water is coordinated double a day for moment alleviation from asthma by Gond tribes of the Nabarangpur region of Odisha. Rout and Sahu (2023) reported that leaves and roots of *A. aspera* were used for the treatment of Scorpion bite and dental problems by the native of Bhawanipatna area, Kalahandi district. Sahu *et al.* (2024) reported that the leaf, root, and stem of *A. aspera* were used for the treatment of Typhoid, toothbrush, and tongue cleaner, respectively by the native of Barpali N.A.C. of Bargarh district of western Odisha, India. Sahu *et al.* (2024) reported that the stem of *A. aspera* was used as a toothbrush by the tribal peoples of Jharigaon block of Nabarangpur district, Odisha, India.

People of Kalahandi district use the plants for various purposes, but till yet no document available on phytochemical screening of this essential plant from the study site. Keeping these in mind the present study deals with the study of documenting the medicinal use and phytochemical screening of the *Achyranthes aspera* L.

Materials and Methods:

Study area

Kalahandi district is nestled in the southwestern part of Odisha, positioned between the latitudes of 19.3N and 21.5N, and the longitudes of 82.20E and 83.47E (Nayak *et al.*, 2024; Sahu et al., 2020; Sahu and Naik, 2022; Rout and Sahu, 2023). It shares its northern borders with Bolangir and Nuapada districts, while to the south; it meets Nabrangpur, Koraput, and Rayagada districts. On the eastern side, it borders Rayagada and Boudh districts. Notably, Kalahandi ranks as the 7th largest district among the 30 in Odisha, covering an impressive area of 8,36,489 square kilometers. The district features two distinct geographical regions: the flat plains and the hilly terrains. The hilly areas, primarily found in the south-western part of the Bhawanipatna subdivision, are rich in diverse flora and fauna. These regions are home to a significant number of rural and tribal communities. A study was conducted across various parts of Kalahandi, where observations and surveys were carried out with locals to explore the medicinal uses of the native plant species found in the area. In order to establish the authenticity of ethnomedicinal uses, the collected data has been cross checked with some scientific literatures (Sahu *et al*., 2010; Sahu *et al.*, 2013, Sahu and Sahu, 2017, 2020).

Preparation of plant extract:

The experiment was conducted in the year 2024 -25 in the college laboratory. The plant parts of *Achyranthes aspera* L were collected from various places of Kalahandi district. It ensured that the plant was healthy and uninfected. The plant parts were washed under running tap water to eliminate dust, other foreign particles and dried. Extracts were analyzed for the presence of active compounds including terpenoids, steroids, saponins, alkaloids, flavonoids, tannins, and coumarin by using various protocols (Rani *et al.*, 2025; Sahu *et al.*, 2024; Sharma *et al.*, 2024; Nayak *et al.*, 2024).

Steroids: To determine the presence of steroids, the Liebermann-Burchard test was conducted. In this test, the extract was combined with a few drops of acetic anhydride, and then boiled. After cooling, concentrated H_2SO_4 was carefully added along the sides of the test tube. The formation of a brown ring at the interface of the two layers was observed. A green coloration in the upper layer and a deep red color in the lower layer would indicate a positive result for steroids.

Tannin: To determine the presence of tannins, one milliliter of water and 1-2 drops of ferric chloride solution were added to 0.5 milliliters of the extracted solution. A blue color indicated the presence of gallic tannins, while a green-black color suggested catecholic tannins.

Terpenoid: The determination of terpenoids was carried out using the Salkowski test. In this test, 5 ml of each extract was mixed with 2 ml of chloroform, and then 3 ml of concentrated H_2SO_4 was carefully added to create a distinct layer. The appearance of a reddish-brown coloration at the interface indicated the presence of terpenoids.

Alkaloid: To determine the presence of alkaloids, Hager's Test was conducted. In this test, a few drops of Hager's reagent, which is a saturated solution of picric acid, were added to the test solution. The formation of a yellow precipitate indicates a positive result for alkaloids.

Phenol: The Phenol Ferric Chloride test was conducted by adding 4 drops of Alcoholic $FeCl_3$ solution to the test extract. The appearance of a bluish-black color indicates the presence of phenol.

Saponin: To determine the presence of saponins, a Foam Test was conducted. In this test, the solution was mixed with water, shaken, and then observed for froth formation. A positive result is indicated by stable froth lasting for 15 minutes.

Coumarin: To determine the presence of coumarin, 3 ml of 10% NaOH was added to 2 ml of the aqueous extract. The formation of a yellow color indicates the presence of coumarins.

Flavanoid: The Flavanoid Lead acetate solution test was conducted, where the test solution, when mixed with a few drops of a 10% lead acetate solution, produced a yellow precipitate.

Results:

Medicinal use of *A. aspera*

The Ethnomedicinal usage of *A. aspera* from the Kalahandi district was enumerated as follows:

- Fresh stems are used as tooth brushes and tongue cleaner. They are used to relieve toothaches.
- Root decoction of this plant with the *Zizyphus mauritiana* is fed to cure chest pain.
- Decoction of leaves applied externally or cuts and wounds.

- The whole plant boiled in water with common salt and the decoction taken for relief from cold and cough.
- Paste of the roots is given orally for the treatment of the cough and bronchitis.
- Powdered root one teaspoonful three times a day for 3-4 days is given for the treatment of fever.
- The root paste mixed with black pepper is given orally for three days for treatment of spermatorrhoea.

Phytochemical screening

Table 1: Qualitative Phytochemical screening of various extracts of different parts of *Achyranthes aspera*.

Different phytochemicals	Methanol				Ethanol				Water			
	L	I	S	R	L	I	S	R	L	I	S	R
Steroid	-	-	-	-	-	-	-	-	-	-	-	-
Tannin	-	-	+	+	-	-	+	+	-	-	+	+
Terpeniod	-	-	-	-	-	-	-	-	-	-	-	-
Alkaloid	+	+	+	+	+	+	-	-	+	+	-	-
Phenol	-	-	-	-	-	-	-	-	-	-	-	-
Flavanoid	+	+	-	-	+	+	-	-	+	+	-	-
Saponin	-	+	+	-	-	+	+	-	-	+	+	-
Coumarin	+	+	+	+	+	+	+	+	+	+	+	-

L: leaf, I: inflorescence, S: stem, R: root

The qualitative study of *Achyranthes aspera* reveals the presence of a number of secondary metabolites. Active component of different parts of *A. aspera* was extracted by two methods i.e. shaking and boiling. As plant extract contains several secondary metabolites so the extract was used for different tests. Test was performed using both extract prepared by shaking and boiling method and documented. Steroid was found to be absent in all extracts prepared by using solvents (methanol, ethanol and water) by both methods. Tannin is present in the shoot and root of several extracts isolated by different solvent using shaking as well as boiling method. Terpenoids are absent in all parts of the plant. Alkaloid is present in methanolic, ethanolic and water extracts of both methods. Phenol was absent in all extract made by shaking method and present in extract using methanol, ethanol and water as solvent and using boiling method. Leaf and inflorescence contain flavanoid. Saponin was present in root and stem parts by shaking method whereas it was found in leaf and inflorescence extract by boiling method. Coumarin was found in all the three extracts. The phytochemical studies with solvent i.e. methanol, ethanol and water extracts of various parts of the plant by shaking and boiling method showed that they possess secondary metabolites. Medicinal plants have received great attention as potential antiperoxidative agents. Plant products are also known for their protective effects by scavenging free radicals and modulating carcinogen detoxification and antioxidant defence systems. The qualitative study of *A. aspera* reveals the presence of a number of secondary metabolites.

Discussions:

The ethnomedicinal usage of *A. aspera* from the Kalahandi district was enumerated as follows: Fresh roots are used as toothbrushes. They are used to relieve toothaches. Root decoction of this plant with the *Zizyphus mauritiana* is fed to cure chest pain in chest. Decoction of leaves applied externally for cuts and wounds. The whole plant boiled in water with common salt and the decoction taken for relief from cold and cough. Paste of the roots is given orally for the treatment of the cough and bronchitis. Powdered root one teaspoonful three times a day for 3-4 days is given for the treatment of fever. The fresh leaves are ground to make a fine paste and placed on to sores of the infant suffering from rickets. The root paste mixed with black pepper is given orally for three days for treatment of spermatorrhoea. Sahu *et al.* (2010) reported that the leaves and roots of *A. aspera* L. used for the treatment of scorpion Bite, dental problem and dysentery by the native of Bargarh district, Odisha. Sahu *et al.* (2013) reported that the leaves of *A. aspera* were used for the treatment of scorpion bite, blood dysentery, and dental problems by the native of Sohela Block, Western Odisha. Sahu and Sahu (2017) reported that small branches of *A. aspera* are cut into small pieces and used as toothbrushes; mixture of the twig is also used as a wash for tooth pain. The dried root powder is used as toothpaste and it is used to treat gum disorders. Further Soak cotton in the extract of 3-4 leaves and apply it on the aching tooth. It also helps in filling and healing up of old time cavities by the natives of Bargarh District, Western Odisha. Sahu *et al.* (2020) stems of aphamarga are used as toothbrushes; a mixture of twigs is also used as a wash to get relief from tooth pain by the tribal community of Kalahandi district. Sahu *et al.* (2020) reported that leaves and roots of *A. aspera* are used for the treatment of scorpion bite, dental problem; dysentery, brushing teeth cures pyorrhea and toothache by the tribal of Kalahandi District, Odisha. Sahu *et al.* (2021) reported that the Sahara tribal groups of Kangaon village of Bargarh district in western Odisha used the leaves, roots and stems of *A. aspera* for the treatment of Typhoid, toothbrush and tongue cleaner. Sahu *et al.* (2021) reported that the root paste of *A. aspera* var. indica L. is applied externally on abdomen for quick delivery by the natives of Bargarh District, Western Odisha. Mishra *et al.* (2022) reported the use of the paste from the whole plant of *A. aspera* is made and applied externally in case of ringworm by the Native of Bargarh District, Odisha, India. Sahu and Mishra (2022) reported that the Root powder of *A. aspera* is added to cow milk and taken to relieve the menstrual disorder by the Native of Bargarh District, Western Odisha, India. Sahu and Sahu (2023) reported that inhalation of dried leaves of *A. aspera* smoke through a chillum (mud pipe utilized for smoking) gives moment alleviation from asthmatic wheezing. The plant separates blended in with equivalent sum honey is coordinated to give youngsters two times every day in a void stomach to control bronchial hack. In constant windedness, 5 gm root powder blended in with 5-7 dark peppers added with a glass of tepid water is coordinated double a day for moment alleviation from asthma by Gond tribes of the Nabarangpur region of Odisha. Rout and Sahu (2023) reported that leaves and roots of *A. aspera* were used for the treatment of Scorpion bite and dental problems by the native of Bhawanipatna area, Kalahandi district. Sahu *et al.* (2024) reported that the leaf, root, and stem of *A. aspera* were used for the treatment of Typhoid, Toothbrush, and Tongue cleaner, respectively by the native of Barpali N.A.C. of Bargarh district of western Odisha, India. Sahu *et al.* (2024) reported that the stem of *A. aspera* was used as a toothbrush by the tribal peoples of Jharigaon block of Nabarangpur District, Odisha, India.

Phytochemical screening is done for analyzing secondary metabolites, which are responsible for curing ailments. Phytochemical screening of the extracts was investigated according to the standard procedure. The petroleum ether, hydroalcoholic, and aqueous extract of bark of A. occidentale and leaves of A. marmelos and whole aerial plant material of *A. aspera* were investigated to preliminary phytochemical screening for the presence of various phytoconstituents, i.e. alkaloids, terpenoids, steroids, flavonoids, carbohydrates, proteins, amino acids, tannins, and phenolic compounds present in them. The results obtained it is clear that all selected plant extracts show the presence of alkaloids, phenols, and flavonoids, in petroleum ether, extract shows the presence of only fats and oil. Hydroalcoholic extract of A. occidentale, A. marmelos, and *A. aspera* shows the presence of alkaloids, glycoside, phenols, and flavonoids. Quantitative analysis is an important tool for the determination of the quantity of phytoconstituents present in plant extracts. For this, TPC and TFC are determined. The hydroalcoholic extract obtained from bark of *A. occidentale*, leaves of *A. marmelos*, and whole aerial plant material of *A. aspera* is subjected to estimate the presence of TPC and TFC by standard procedure (Brijyog *et al.*, 2019). Phytochemical screening on other species were done by various authors like *Drimia indica* (Rani *et al.*, 2025), *Hibiscus* (Sahu *et al.*, 2024), *Marsilea minuta* L. (Sharma *et al.*, 2024), *Tridax procumbence* (Nayak *et al.*, 2024), etc.

References:

1. Bharathi NM, Sravanthi V, Sujeeth S, Kalpana K, Santhoshi P, Pavani M, *et al.* (2013): In vitro anthihelminthic activity of methanolic and aqueous extracts of *Achyranthes aspera* Linn.(Amaranthaceae) stems, Int J Pharm Sci., 3(2): 181-184.
2. Brijyog, Singh LP, Kumar S, and Verma S (2019): Phytochemical screening and antioxidant potential of *Anacardium occidentale*, *Achyranthes aspera*, and *Aegle marmelos*. Asian J Pharm Clin Res, 12(8): 202-205.
3. Dwivedi SN (2003): Herbal remedies among tribals of sidhi district of Madhya Pradesh. J. Econ. Tax, 28(3): 675-686.

4. Edwin S, Edwin Jarald E, Deb L, Jain A, Kinger H, Dutt KR, Raj A. (2008): Wound healing and antioxidant activity of *Achyranthes aspera*, *Pharmaceutical Biology*, 46(12): 824-828.
5. Khan MTJ, Ahmad K, Alvi MN, Noor-Ul-Amin, Mansoor B, Saeed MA, Khan FZ and Jamshaid M (2010): Antibacterial and irritant activities of organic solvent extract of *Agave americana* L., *Albizzia lebbeck* Banth., *Achyranthes aspera* L., and *Abutilon indicum* L.- a preliminary investigation, Pakistan Journal of Zoology, 42(1): 93-97.
6. Mishra S, Sahu M, and Sahu AR (2022): Medicinal plants used for the treatment of various skin disorders by the native of Bargarh district, Odisha, India. In Recent Trends and Advances in Medicinal Plants Research, Soni PK (eds.) PK Publishers and Distributors, 4th Pustak Kartar Nagar, New Delhi, Chapter 11, Pp. 121-130. (ISBN: 978-81-953735-8-1).
7. Nayak NR, Behera G, Sahu AV, Pujhari T, Puhari S, Das A, Singhdeo D and Sahu AR (2024): Study of freshwater Algal biodiversity in and around of Bhawanipatna, Kalahandi, Odisha. International Journal of Research Publication and Reviews. 5(6): 1793-1799.
8. Nayak NR, Pattnayak A and Sahu AR (2024): Screening for Phytochemicals, antimicrobial and anticoagulant activity of aqueous extract of *Tridax procumbence.* In Research and Reviews in Plant Sciences Volume II; Srivastava MP, Bangar MA, Chachad D, and Kumar AR (Ed.). Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, INDIA. Pp. 115-126.
9. Paul D, Bera S, Jana D, Maiti R, and Ghosh D (2006): In vitro contraceptive spermicidal activity of a composite extract of *Achyranthes aspera* and Stephania hernandifolia on human semen. Contraception, 73(3): 284-288.
10. Prasad SHKR, Swapna NL, Anthonamma K, Rajasekhar and Madanprasad D (2009): Antimicrobial activity of *Achyranthes aspera* and *Aerva lanata* leaf and callus extracts. Biosciences Biotechnology Research Asia, 6(2): 887-891.
11. Rani JJ, Tripathi G, Pattanayak S, Boxi S, Rout S, Kumar S and Sahu AR (2025): Phytochemical and cytotoxic analysis of bulbs of *Drimia indica* (Jungli piyaz): a medicinal plant of Asparagaceae. In Plants and Secondary Metabolites, Hossain E, Roy BC, Jena N and Kumar S (Eds.), Volume 4, Chr. 6, P.p. 52-61. DOI: https://doi.org/10.5281/zenodo.14845056.
12. Rout P, and Sahu AR (2023): Medicinal uses of selected plants by the native of Bhawanipatna of Kalahandi district, South-Western Odisha, India. In Frontiers in Life Science Volume X; Parimala B, Mishra P, Yadav KK, and Sahu AR (Ed.). Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, INDIA. Chapter 7, Pp. 39-46. (ISBN: 978-93-88901-35-2).

13. Sahu AR, and Mishra S (2022): Plants used for the treatment of Gynecological disorders by the native of Bargarh district, Western Odisha, India. In Recent Trends and Advances in Medicinal Plants Research, Soni PK (eds.), PK Publishers and Distributors, 4th Pustak Kartarz Nagar, New Delhi, Chapter 6, Pp. 71- 76. (ISBN: 978-81-953735-8-1).
14. Sahu AR, and Naik D (2022): Documentation of Exotic Plants from Saraswati Degree Science College Campus and Adjoining Areas in Bhawanipatna, Kalahandi District, Odisha. International Journal of Creative Research Thoughts, 10 (1): d697-d706. (http://doi.one/10.1729/Journal.29037).
15. Sahu AR, and Sahu M (2023): A preliminary Report on Ethnomedicinal Study of Plants Used to Treat Asthma by the Gond Tribes of Nabarangpur District, Odisha, India. In Frontiers in Life Science Volume X; Parimala B, Mishra P, Yadav KK, and Sahu AR (Ed.). Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, India. Chapter 1, Pp. 1- 10. (ISBN: 978-93-88901-35-2).
16. Sahu AR, Behera N and Mishra SP (2010): Use of Ethnomedicinal Plants by Natives of Bargarh District of Orissa, India. Ethnobotanical Leaflets, 14: 889-910.
17. Sahu AR, Mishra S, Sahu M and Nayak NR (2020): A preliminary report on ethnomedicinal uses of different plants for oral care in Kalahandi district, Odisha. International Journal of Applied Research, 6 (6): 265-268 (DOI: 10.22271/allresearch.2020.v6.i6e.6793).
18. Sahu AR, Nayak AK and Panigrahi SK (2013): Survey of some important ethno-medicinal plants of Sohela Block, Western Odisha, India. Life Sciences Leaflets, 11(11): 1-9.
19. Sahu AR, Nayak NR, and Ekka NJ (2024): A mini-review on phytochemical screening, biological activity, and therapeutic capability of *Hibiscus*: An ornamental plant species. In Research and Reviews in Plant Sciences; Chachad D, Mishra S, Mahishi P, and Sahu AR (Ed.). Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, INDIA. Volume IV, Pp. 72-80.
20. Sahu AR, Sahu M, and Raal A (2021): An Ethnobotanical Study on Native Plants of Bargarh of Western Odisha, India in relieving Urogenital ailments. Ethnobotany Research & Applications, 21:29 (http://dx.doi.org/10.32859/era.21.29.1-11).
21. Sahu AR, Sahu M, Mishra S, Ekka NJ (2021): A preliminary Report on Ethnomedicinal uses of Selected Plants by *Sahara* Tribal Groups of Kangaon Village of Bargarh District in Western Odisha. Journal of Medicinal Plants Studies, 9(3): 238-242. DOI: https://doi.org/10.22271/plants.2021.v9.i3c.1300.
22. Sahu AR, Sahu M, Nayak NR and Sahoo TR (2020) Medicinal Plants of Saraswati +3 Science College, Bhawanipatna Campus and it’s adjacent areas, Kalahandi district, South-Western Odisha, India. World Journal of Pharmacy and Pharmaceutical Sciences, 9 (1): 1738-1752. (DOI: 10.20959/wjpps20201-15408).

23. Sahu M and Sahu AR (2017): A Preliminary Report on the Traditional Practice for Dental and Oral Health Care in Bargarh District of Western Odisha, India. Journal of Medicinal Plants Studies, 5(5):120-125.
24. Sahu M, and Sahu AR (2024): Use of Chewing Sticks in the Era of Toothbrush: A Case Study from Jharigaon Block of Nabarangpur District, Odisha. In Plant Science: From Fundamentals to Advanced Research; Gautam PK, Dewangan N, Ulhe PP, Patil PD (Ed.) Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, INDIA. (ISBN: 978-93-95847-68-1) Vol. II, Pp. 127-134.
25. Sahu R, Nayak NR, Behera G, Ekka NJ and Sahu AR (2024): Ethnomedicinal Study of Selected Plants Used by the Native of Barpali N.A.C., Bargarh District, Odisha. In Trends and Innovations in Environmental Science; Murthy K, Meena SK, Kumaran P, Varale Y(Ed.). Bhumi Publishing, Nigave Khalasa, Kolhapur 416207, Maharashtra, INDIA. (ISBN: 978-93-95847-41-4), Pp. 142-152.
26. Sharma A, Lal S, Sharma BP, Rathore S, Sahu AR, Jena N and Kumar S (2024): Phytochemical analysis of *Marsilea minuta* L.: an aquatic medicinal plant. In Medico Bio-wealth of India, Vimala K, Choudhary JR and Das SK(Eds.), APRF Publishers, India. Vol. 15, Chr. 2, P.p. 11-20. DOI: https://doi.org/10.5281/zenodo.11123606.
27. Sharma S, Shrivastava PN, Saxena RC (2006): Antimicrobial activity of saponins isolated from *Achyranthes aspera* against Staphylococcus aureus. Asian J Chem, 18 (4): 2766-2770.
28. Shibeshi W, Makonnen E, Zerihun L, Defella A (2006): Effect of *Achyranthes aspera* on foetal abortion, uterine pituitary weights serum lipids and hormones. African Health Science, 6(2): 108-112.
29. Sutar NG, Sutar UN, Sharma YP, Shaikh IK, and Kshirsagar SS (2008): Phytochemical investigation and pharmacological screening of leaves of *Achyranthes aspera* Linn. as analgesic and antipyretic. Biosciences Biotechnology Research Asia, 5(2): 841-844.
30. Zahir AA, Rahuman AA, Kamaraj C, Bagavan A, Elango G, Sangaran A, Kumar BS (2009): Laboratory determination of efficacy of indigenous plant extracts for parasites control. Parasitology Research, 105(2): 453-461.

THERMAL NEUTRON RADIOGRAPHY AND TOMOGRAPHY

Poonamlata S. Yadav

Maharashtra College of Arts, Science and Commerce, Mumbai, India

Corresponding author E-mail: poonamlatay@gmail.com

Abstract:

In recent years, thermal neutron radiography and tomography have gained much attention as one of the nondestructive testing methods. However, the application of thermal neutron radiography and tomography hindered by their technical complexity, radiation shielding, and time-consuming data collection processes. Monte Carlo simulations have been developed in the past to improve the neutron imaging facility's ability. In this present paper, has been discussed about the thermal neutron radiography and tomography with deterministic simulation approach and demonstrated to simulate neutron radiographs numerically. This approach has made the simulation of neutron radiographs much faster than by previously used stochastic methods (i.e Monte Carlo methods). The major problem with neutron radiography and tomography simulation is finding a suitable scatter model.

Keywords: Thermal Neutron Radiography, Neutron Tomography, Monte Carlo Simulations, Radiation Shielding, Thermal Neutron Imaging

1. Introduction:

Neutron radiography is a well-established method of non-destructive testing (NDT) which has been there since 1950's [1]. In the last few years, neutron imaging has gained much more attention over other methods of imaging. Neutron interacts with materials in a complementary way compared to the X-ray imaging. The materials with high atomic numbers are opaque in X-ray imaging, compared to the neutron. This mode of imaging is preferred in the areas where it is needed to locate a material of low atomic number inside of a material with high atomic number. In many fields of research and industry it is important to locate moisture, crack, bubble flow, etc., inside a system. For example, in the field of archeology, it is sometimes important to determine the content of ancient sculptures [2], thermal neutron imaging is a core part of studies involving water content determination [3]. In nuclear engineering, neutron radiography and tomography is widely used for the inspection of fuel cells and neutron radiography is also used in thermal hydraulics to determine void fraction in pipes [4-5]. Thermal neutrons have high capability to distinguish between different materials as the thermal neutron cross sections are significantly different from low atomic number materials to high atomic number materials and even from one isotope to another. The attenuation probabilities of materials in case of thermal neutrons are not dependent on their atomic numbers. This property of thermal neutrons makes them suitable in non-destructive testing. So far, the techniques that have been used for simulating neutron radiography are stochastic methods, such as Monte Carlo methods [6].

Simulating a neutron imaging facility's performance is of utmost importance. Simulating the images shows whether the imaging set up works efficiently or not. Based on the results of imaging facility, suitable and faster method needs to be developed. Monte Carlo methods need both significant time and resources to solve neutron imaging problem. To make neutron radiography more effective a faster method needs to be implemented. A deterministic method has been implemented to simulate thermal neutron radiography which is significantly faster than previously used methods. There is one disadvantage of using thermal neutrons as a mean to image hydrogenous materials such as, water, or any such biological sample. Hydrogen acts as a highly scattering medium in case of thermal neutrons. In case of imaging, scattered neutrons can degrade the quality of the image and introduce effect such as blurring of image at sharp edges. Scattering adds a neutron distribution to the detected signal, which makes the reconstruction procedure very challenging. So, before reconstruction of images, the effect of scatter needs to be removed or minimized without affecting signal quality. Therefore, a suitable scatter removal algorithm needs to be developed. The scatter correction methods available till date uses Monte Carlo methods such as MCNP to simulate the scatter effect. In case of neutron imaging MCNP takes a huge time to run.

2. Characteristics of Neutrons

As a fundamental particle, neutron has the ability to provide a stream of unique characteristics which are proved to be essential in the imaging community. In this section, those attributes of neutrons are discussed. These properties of neutrons interacting with matter give underlying ideas of neutron imaging. As one of the main components of an atom, neutron was discovered in 1932 by J. Chadwick [7]. Neutron is electrically neutral, which makes it an attractive both in scattering and imaging applications. It interacts primarily with nuclei because of its charge neutrality; it is highly penetrating and is suitable enough to penetrate materials with higher atomic mass. These properties make neutrons suitable for imaging light materials, or investigating the inside of a large assembly in a nondestructive way. Another important fundamental property of neutron is its mass, (m_n = 1.6749 × $10^{-27} Kg$), which gives the neutron a de Broglie wavelength compared to the atomic distances in room temperatures (thermal energy range). The de Broglie wavelength, λ in units of nm, is given by

$$\lambda = \frac{h}{m_n v} = 395.6/v \qquad (1)$$

Where, h = 6.6261 × $10^{-34} J - s$ is the Planck's constant and v is the neutron velocity in ms^{-1}. The neutron energy is given by:

$$E = \frac{1}{2m_n v^2} = 5.2770 \times 10^{-6}\, v^2 \qquad (2)$$

A neutron in thermal energy (room temperature 300K) will have a velocity of approximately 2224 ms^{-1} and corresponding wavelength of 0.18nm. Neutrons are typically produced either in reactors via the nuclear fission or in spallation neutron sources (where a high energy proton beam is incident on a heavy metal and produces neutrons). These neutrons are in fast energy range (see Table 1). Thermal neutrons are more suitable for imaging purpose because they are easier to be detected than fast neutrons. The neutrons need to be slowed or cooled down. Moderators are used to convert fast neutrons to thermal or cold energy range. Generally, hydrogen or hydrogenous materials, graphite, etc., are used for moderation.

Table 1: Neutron properties at various energy ranges

Energy classification	Energy range (meV)	Velocity ($ms{-}1$)	Wavelength (nm)
Ultra-Cold	0.00025	6.9	57
Cold	1	437	0.9
Thermal	25	2187	0.18
Epithermal	1000	12,832	0.029

3. Interactions with Matter and Cross Section

In thermal neutron imaging the principle lies in neutron interaction that attenuates a ray or beam of neutrons coming from a source. Neutrons can be removed from the incident beam by the object by two phenomena, absorption and scattering. Figure1 illustrates the attenuation of neutron beam incident perpendicularly on a thin sample of thickness dx which is placed at a distance x from the source. The thickness is small enough so that it is only one atom layer thick and the neutrons can interact with all the atoms involved.

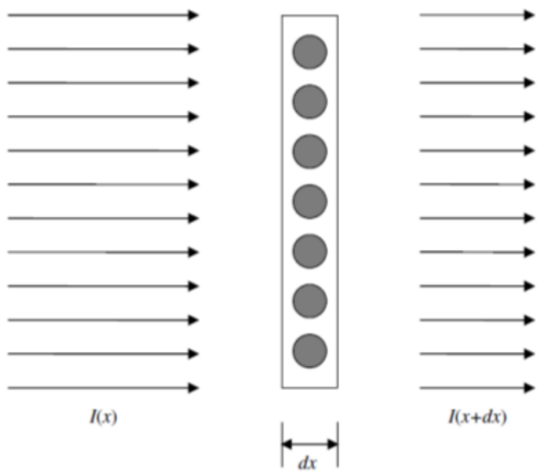

Fig. 1: Neutron interaction with matter

Let $I\ (x)$ be the incident neutron flux, and $(x + dx)$ be the transmitted flux. Let N be the number density of atoms in that layer. It is assumed that the atoms are particles of radius r. The neutron attenuation is given by the fractional area occupied by all the atoms in that layer, which is equal to $dx.\ N\pi r^2$. This gives:

$$I(x + dx) = I(x)(1 - dx.N\pi r^2) = (x)(1 - dxN\sigma) \qquad (3)$$

Where, σ is defined as the microscopic cross section. Microscopic cross section is defined as the effective interaction area between the neutron and the nucleus.

From Eq.3 the rate of change of I(x) is given by:

$$\frac{dI(x)}{dx} = -N\sigma(x) \qquad (4)$$

And the solution for I(x) is given as below:

$$I(x) = I_0 \exp(-N\sigma\, x) \qquad (5)$$

Where, I_0 is the incident neutron flux. The product $N\sigma$ is known as the macroscopic cross section. For an object with more than one material, the macroscopic cross section is the sum over all the macroscopic cross sections.

The neutron-nucleus interaction is of quantum mechanical in nature. Neutron interacts with an object either via absorption or scattering. The total microscopic cross section is given by

$$\sigma_t = \sigma_a + \sigma_s \qquad (6)$$

Where, σ_a and σ_s are absorption and scattering cross section respectively. The neutron scattering cross section can be further divided into coherent and incoherent scattering. In coherent scattering, neutrons that are scattered primarily by different nuclei combine with one another to produce an interference pattern that depends on the relative locations of the atoms in the material. Incoherent scattering is the case when there is more than one isotope present in one sample. Neutrons interact with matter in five different ways:

3.1 Elastic scattering

Neutron collides with the nucleus and loses its kinetic energy. Neutron loses more energy to heavier materials than to lighter materials. Elastic scattering is the most important phenomena to produce thermal or cold neutron from fast neutron sources.

3.2 Inelastic scattering

Inelastic scattering is similar to elastic scattering but here when the neutron collides with the atomic nucleus it deposits part of its energy to the nucleus and takes it to an excited state. After collision, the nucleus emits gamma rays to get back to the ground state. This type of scattering is not preferred in neutron radiography as it causes gamma emission which is considered as noise.

3.3 Neutron capture

A neutron can be absorbed by the atomic nucleus to increase its atomic number by one. The new nucleus most likely becomes a radioactive nucleus and emits radiation.

3.4 Charged particle emission

This phenomenon is generally occurred by fast neutrons, where charged particles are emitted upon the incidence of neutrons.

3.5 Fission

Fission occurs when nucleus upon incidence of a neutron, the nucleus divides into two nuclei and emits more than one neutron in process.

Here, thermal neutrons are used as the source. Only the scattering and absorption phenomena are dominant in thermal neutron imaging. Elastic scattering is predominant in thermal neutron energy. The corresponding thermal neutron cross section of different materials (ranging from atomic number 1-100) is shown in Figure 2.

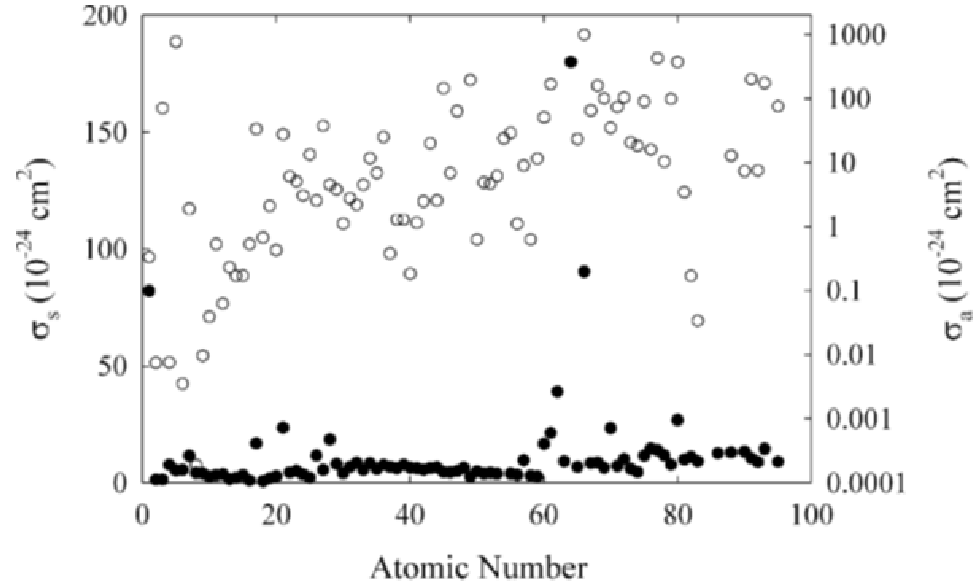

Fig. 2: Thermal neutron scattering and absorption cross section distribution

From Figure 2, it is clear that the scattering cross section and the absorption cross section does not have any linear relationship with the atomic number of the materials, and the scattering cross section is very high in case of lower atomic number materials such as hydrogen. Monochromatic energy source of energy 0.0253eV has been used as a source. This is the most probable energy of a thermal neutron energy distribution. Thermal neutron energy distribution is a Watt distribution.

The velocity distribution function of thermal neutron energy range is given by the following equation:

$$\Phi(\mathrm{v})\mathrm{dv} = \Phi \frac{2}{v_T^4} v^3 \exp\left(-\left(\frac{v^2}{v_T^2}\right)\right) \tag{7}$$

Where, $\Phi(v)$ is the neutron velocity flux distribution, v is the neutron velocity and v_T is the neutron velocity at temperature equal to 293.6K ($\approx 2200 m/s$).

4. Neutron Imaging and Its Simulation

The idea of imaging is to create a contrast between different elements based on their inherent and unique properties like mass attenuation coefficients, conductivity, and microscopic cross sections. Neutron radiography uses the microscopic cross section property of materials to generate the radiograph. The main sources of image degradation in neutron radiography are scattering degradation, geometric degradation, displacement degradation, neutron spectral degradation and detector degradation. In neutron radiography the main mathematical equation can be expressed as

$$\frac{\mathrm{I}}{I_0} = \exp\left(-\sum\nolimits_t (E).x\right) \qquad (8)$$

Where, $\sum_t(E)$ is the total cross section of the material to be imaged. I and I_0 are the neutron intensity after and before incidence. The thickness of the material is defined as x. It is to be noted that the total material cross section is energy dependent.

There has been a lot of work in the area of neutron radiography using MCNP. Early important work was from Segal *et al.* [8] when they published their work regarding the calculation of point spread function of thermal neutron radiograph. The contribution of scattered neutron in the radiographed object was calculated using MCNP. But this work was insufficient as they failed to provide accurate distribution of dimensions and thickness. Murata *et al.* [9] developed a method to to eliminate the effects of scattered neutrons from NR (Neutron radiography) by using a Cd grid. Raine *et al.* [10] developed a correction algorithm using MCNP which determines the scattering contribution. But this work was limited only to high resolution with objects less than 2 centimeters in vertical or horizontal directions. Kardjilov *et al.* (2005) [11] derived a procedure where they simulated the point scattered function for different position and thickness and property of target materials. Then they formulated a Gaussian function which fits the scattered neutron distribution of the target material at different distances from the source and different thickness of the material. Once the distribution of scattered neutrons was obtained in mathematical terms it was subtracted from the original radiograph to obtain scatter free image. The advantage of this work was once the distribution of scattered neutrons were obtained in terms of Gaussian distribution it eliminated the use of MCNP simulation each time a radiograph needs to be generated. Montaser Tharwat *et al.* [6] devised a methodology using MCNP and MATLAB together for radiograph generation.

The scattered neutron distribution was computed using MCNP and flux distribution of each pixel was determined individually which corresponds to the scattered neutrons and then a software tool named ImageJ from MATLAB was used to efficiently subtract this effect. LIU Shu-Quan *et al.* [12] designed a method for scattering correction for fast neutrons at the NECTAR (Neutron Computerized Tomography and Radiography) facility at Germany. They calculated the scattered fast neutron distribution at different distance and thickness using MCNP and subtracted it from original image to obtain scatter free image. The scattering distribution simulation took 10 hours with 64 CPUs parallel computing to obtain a PScF data with simulating 10^8 neutrons and with error less than 5%. The improvements that can be done from the previous works are first to find a method to run a huge number of particle history within a small amount of time. Generation of scattered neutron distribution using MCNP and subtraction is a time consuming procedure. If it needs to be implemented commercially a faster simulation method needs to be developed. The variance reduction methods in MCNP can be used to run the simulation very fast. The subtraction algorithm needs to be improved in such a way so that not only scattered neutron effects are eliminated other imaging irregularities should also be removed. An optimization between image quality and run time or particle history has to be analyzed so that a certain quality of image can be obtained with minimal cost.

When the image of an object is generated a spectrum of neutron energy is used. It can be analyzed which spectrum or range of energy gives the best resolution or image quality. It is also dependent on the thickness of the material and distance from the source and its material properties (cross section). So if some work is done as to which range provides minimum error it will more effective.

5. Thermal Neutron Radiography and Tomography

Thermal neutron radiography and tomography is a powerful tool of non-destructive imaging techniques. The images are formed due to attenuation of thermal neutron beam when it is propagated through the material to be visualized. Neutron radiography is in used since shortly after the discovery of neutrons by Chadwick in 1932[7]. Different Radioisotopes sources were used for neutron radiography [13]. Later accelerators and nuclear reactors were used as neutron source. Different types of position-sensitive detectors are implemented. Even with advanced instrumentation for radiography it lacked in one broad area which was all the information of a three dimensional object was restricted to two dimensional image. It was hard to distinguish between two materials with similar attenuation property. The issue was solved by the pioneer work of Hounsfield [14], who implemented computed tomography based on the early mathematical foundation provided by Radon in 1917[15].

5.1. Principles of Neutron Radiography

Radiography implements two dimensional detection of transmitted neutron beam in a plane perpendicular to the direction of beam propagation (Figure 3). This creates a two-dimensional shadow of the object. The shadow or radiograph properties vary based on the thickness and integral attenuation properties of the material being imaged. The transmission, is the ratio of the transmitted beam intensity I, and incident beam intensity I_0.

$$T = \frac{\mathrm{I}}{I_0} \tag{10}$$

For any path along the transmission, according to the basic law of attenuation of radiation

$$\mathrm{I} = I_0 \exp\left(-\int \mu ds\right) \tag{11}$$

Where, μ is the local linear attenuation coefficient, and s is the propagation path.

The attenuation co-efficient is a material property and is given by

$$\mu = \frac{\sigma\rho N_A}{M} \quad or\ \mu = \frac{\Sigma_i \sigma_i \rho_i N_A}{M_i} \tag{12}$$

For single elements and for multiple elements respectively, where σ is the total Interaction cross – section, ρ is the density of the material, N_A is the Avogadro's number, and M is the molar mass.

Neutrons passing through the object can interact with it in three ways: (1) absorption by the material, (2) scattering (coherent and incoherent) and (3) pass through the material without interaction (un-collided neutrons). In case of absorption the neutrons get lost or attenuated. In case of scattering, they slow down or change directions. Un-collided neutrons are the neutrons that reach the detector. Scattered neutrons also can reach the detector from a different direction and degrade image quality and create blur.

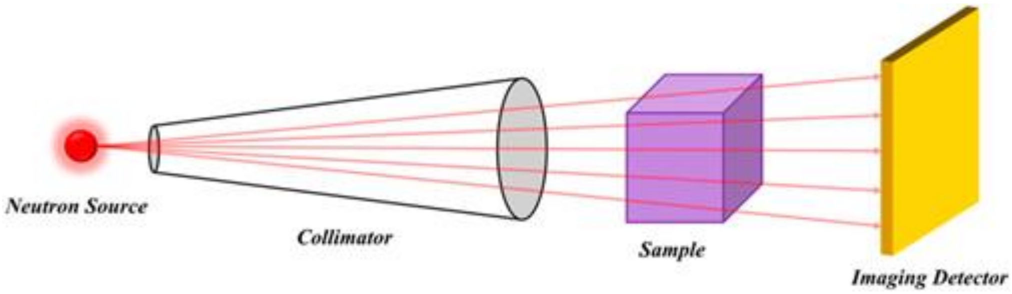

Fig. 3: Schematic of a standard neutron radiography system

5.2. Principles of Neutron Tomography

Computerized tomography is a technique which can reconstruct the three dimensional image of the object from different radiographic images taken from different angles in small successive manner. These images can be mathematically manipulated to reconstruct a three dimensional image. One of the fastest and popular methods of reconstruction is the filtered back projection algorithm (FBP). In this work FBP algorithm has been used to reconstruct neutron images. All projections are first arranged into a new set of images such that the n'th pixel row of each projection is now stored sequentially in an individual image, also known as a sinogram. Every sinogram contains all the attenuation information for all possible angles. An implementation of inverse two dimensional Radon transform is then applied to calculate a cross sectional slice from each sinogram. Each reconstructed slice lies in a plane perpendicular to the axis of rotation. Collecting all slices into an image stack represents the three-dimensional attenuation distribution of the object. The image stack can be used to emphasis certain specific volume based on requirements.

The geometry of the imaging set up is influenced by the sample size and the pixel width (smallest possible scanning length or spatial resolution). The flux and the wavelength spread are directly related, the smaller the wavelength spread, the smaller the flux. This is also true for the spatial resolution; the smaller the pixel size (higher spatial resolution), the smaller the integrated flux at the pixel. Therefore, for attenuation based neutron imaging, full spectrum is used to get statistically significant results. For monochromatic imaging, generally (1-5%) $\Delta\lambda/\lambda$ is required to distinguish between materials. Scattering phenomena causes unwanted image artifacts in case of neutron radiography. They decrease the sharpness of the image. The disadvantage of neutron imaging over X-ray imaging is that X-ray scattering cross section is regular and is related to the atomic number of the material being imaged, whereas neutron scattering cross sections are atomic number independent and statistical in nature. While that particular property makes neutron imaging suitable for locating light materials under heavy materials, it makes the elimination of scatter artifacts challenging.

For neutron radiography and tomography, collimators or slits are used to direct the radiation towards the object and get a point to point image. In order to obtain neutron image in a certain exposure time minimum number of neutron flux should be available. The exposure period is dependent on the problem and can vary from few second to several minutes. The exposure time and the neutron flux should be optimized together.

6. Neutron Sources and Facilities

There are three main sources of neutrons: nuclear reactors, spallation neutron sources, and radioactive sources emitting neutrons. It might seem that it is not relevant where the neutrons are coming from, but neutron source spectrum has a massive impact on the imaging modality. The energy distribution of neutron source and background noise of the source (fast neutrons, gamma rays, delayed neutrons) can alter the quality of the image in a substantial way. They can also interact with the detector electronics. Therefore it is very important to choose which type of source to be used based on the requirement of the experiment. Nuclear reactors use fission to produce neutrons. Spallation neutron sources produce neutrons by hitting a target material with high energy protons. Both nuclear reactor and spallation source produce neutrons with the energy range of few mega electron volts. However, in neutron imaging generally thermal or cold neutrons are used. A moderator must be used in order to slow down these fast neutrons. Neutrons can be produced from the radioactive sources, for example, Cf-252 isotope produce neutrons.

Conclusion:

The methods discussed in this paper are very useful for simulation of neutron radiography and tomography. It can be used to design and optimize a neutron imaging system. Also, it is useful in developing scatter correction and noise removal algorithms to improve the quality of neutron imaging. In a highly scattering hydrogenous medium, such as water, biological samples, etc., the scatter contamination is also significant, and must be corrected. Although scattering may reduce the noise effect as it increases the number of neutrons detected, it degrades the contrast significantly. Empirical parameters and the Gaussian function, which are dependent on materials, can be pre-determined for most materials with similar thermal neutron interaction cross section.

References:

1. Berger, H., & Iddings, F. (1998). *Neutron radiography – A state-of-the-art report* (NTIAC-SR-98-01). Nondestructive Testing Information Analysis Center, Austin, TX.

2. Fiori, F., Giunta, G., Hilger, A., Kardijlov, N., & Rustichelli, F. (2006). Non-destructive characterization of archaeological glasses by neutron tomography. *Physica B: Condensed Matter, 385–386*(2), 1206–1208.
3. Boo, J. J., et al. (2015). Neutron radiography for the study of water uptake in painting canvases and preparation layers. *Applied Physics A*.
4. Craft, E., et al. (2014, October). Neutron radiography of irradiated nuclear fuel at Idaho National Laboratory. *Physics Procedia, 69*, 483–490.
5. Putra, N., Ramadhan, R. S., Septiadi, W. N., & Sutiarso. (2015). Visualization of boiling phenomena inside a heat pipe using neutron radiography. *Experimental Thermal and Fluid Science, 66*, 13–27.
6. Tharwat, M., Mohamed, N., & Mongy, T. (2014). Image enhancement using MCNP5 code and MATLAB in neutron radiography. *Applied Radiation and Isotopes, 89*, 30–36.
7. Chadwick, J. (1932). Possible existence of a neutron. *Nature, 129*, 312.
8. Segal, Y., Gutman, A., Fishman, A., & Notea, A. (1982). Point spread function due to neutron scattering in thermal neutron radiography of aluminum, iron, zircon, and polyethylene objects. *Nuclear Instruments and Methods, 197,* 557.
9. Murata, Y., et al. (1992). Two-dimensional neutron image excluding the effect of scattered neutrons. *Gordon and Breach Science Publications, 4*, 583–590.
10. Raine, D. A., & Brenizer, J. S. (1996). A scattering effect correction for high resolution neutron radiography and computed tomography. In *Fifth World Conference on Neutron Radiography*, Berlin, 17–20.
11. Kardijlov, N., et al. (2003). Further developments and applications of radiography and tomography with thermal and cold neutrons.
12. Liu, S.-Q., et al. (2013). Corrections on energy spectrum and scatterings for fast neutron radiography at NECTAR facility. *Chinese Physics C, 37*(11), 81–70.
13. Chankow, N. (2012). Neutron radiography. In M. Omar (Ed.), *Nondestructive testing methods and new applications*. InTech. https://doi.org/10.5772/2481
14. Hounsfield, G. N. (1973). Computerized transverse axial scanning (tomography). Part 1: Description of system. *British Journal of Radiology, 46*, 1016–1022.
15. Madych, W. R. (2004). Radon’s inversion formulas. *Transactions of the American Mathematical Society, 356*(11), 4475–4491.

QUBITS ENGINES OF CHANGE WITH ENTANGLING INNOVATION: PIONEERING CLEAN AND SUSTAINABLE ENERGY THROUGH NEXT-GEN QUANTUM COMPUTING

Debabrata Sahoo

DAV School of Business Management, Bhubaneswar, Odisha, INDIA

Corresponding author E-mail: dr.dsahoo.1612@gmail.com

Abstract:

In an era where climate change demands urgent action, quantum computing emerges as a beacon of hope, blending the esoteric principles of quantum mechanics with the practical imperatives of sustainability. This chapter explores how quantum computing revolutionizes sustainable energy systems by optimizing renewable energy grids, enhancing battery technologies, and accelerating materials discovery for clean energy. Unlike classical computing, quantum systems leverage superposition and entanglement to solve complex problems at unprecedented speeds, offering transformative solutions for energy efficiency and carbon reduction. Through real-world case studies, such as IBM's quantum simulations for battery chemistry and Google's optimization of wind energy, we illustrate the technology's potential to reshape the energy landscape. By bridging science, technology, and sustainability, this chapter envisions a future where quantum leaps propel humanity toward a greener, more resilient world. Quantum computing promises to revolutionize sustainable energy by solving problems that classical computers struggle with, from optimizing grid performance to discovering novel materials for energy storage. This chapter explores the potential of quantum technologies to accelerate the transition to a low-carbon future. We begin by tracing the emergence of quantum computing and its relevance to sustainability, then delve into specific applications in renewable energy optimization, battery chemistry, and clean-energy materials discovery. Through real-world case studies—such as Google's wind farm optimization, IBM's battery simulations, and Oxford PV's perovskite breakthroughs—we illustrate how quantum approaches are already yielding insights. We also address the technical, economic, and ethical challenges facing quantum green initiatives, and outline a roadmap for future research and collaboration. By marrying quantum innovation with environmental stewardship, we chart a path toward truly transformative energy solutions.

Keywords: Quantum Computing, Sustainable Energy, Renewable Energy, Quantum Mechanics, Optimization, Clean Technology, Climate Change, Materials Discovery, Simulation

1. Introduction:

The Quantum Dawn of Sustainability

Imagine a world where energy flows as effortlessly as a river, where renewable grids hum with precision, and where batteries store sunlight with the efficiency of nature itself. This is not a distant dream but the promise of quantum computing—a technology rooted in the mysterious dance of subatomic particles, poised to redefine our sustainable future. As the planet grapples with climate change and resource depletion, quantum computing offers a paradigm shift, harnessing the power of quantum mechanics to solve energy challenges those classical computers struggle to address. This chapter embarks on a journey through the quantum realm, exploring how this revolutionary technology optimizes renewable energy systems, enhances energy storage, and accelerates the discovery of sustainable materials. By weaving together science (quantum mechanics), technology (quantum computing), and sustainability (energy solutions), we illuminate a path toward a greener, more resilient world.

The urgency of sustainability demands interdisciplinary innovation. Quantum computing, with its ability to process vast datasets and solve complex optimization problems, is uniquely positioned to address energy challenges. From designing smarter grids to discovering next-generation solar cells, this technology bridges theoretical science with practical outcomes, offering hope for a carbon-neutral future. This chapter will delve into the mechanics of quantum computing, its applications in sustainable energy, and its transformative potential, supported by real-world examples and a vision for what lies ahead.

The global imperative to decarbonize energy systems is colliding with the limitations of classical computing. Many optimization and simulation tasks—such as finding the most efficient configuration of wind turbines or exploring vast combinatorial spaces of battery materials—are intractable at the scale required for climate impact. Quantum computing offers a new paradigm: qubits harness superposition and entanglement to process information exponentially faster for certain problem classes. This quantum dawn arrives as the world demands leap-frog innovations to meet net-zero targets.

In this chapter, we chart a course through quantum-enabled pathways to a greener future. Section 2 explains the science behind quantum advantage and why these features matter for sustainability. Section 3 examines quantum algorithms applied to grid optimization and market forecasting, featuring Google's wind optimization and E.ON's market modeling. Section 4 explores quantum simulations of battery chemistry and circular-economy recycling, with insights from IBM-Mercedes and QuantumScape. Section 5 investigates quantum-driven materials discovery for solar cells and carbon capture, spotlighting Oxford PV and BP collaborations. We conclude by discussing the challenges—error correction, hardware scaling, and cost—and opportunities for interdisciplinary research and public-private partnerships. Our aim is to illuminate how quantum leaps can yield practical solutions, accelerating the transition toward a sustainable tomorrow.

2. Understanding Quantum Computing: The Science Behind the Leap

Quantum computing is a revolutionary paradigm that leverages the principles of quantum mechanics—superposition, entanglement, and quantum tunneling—to perform computations far beyond the capabilities of classical computers. Unlike classical bits, which represent either 0 or 1, quantum bits (qubits) exist in a superposition of states, enabling simultaneous processing of multiple possibilities (Nielsen & Chuang, 2010). Entanglement creates correlations between qubits, allowing quantum computers to solve complex problems—such as optimization and simulation—with exponential speed.

2.1. Why Quantum for Sustainability?

Energy systems are inherently complex, involving variables like weather patterns, grid demand, and material properties. Classical computers struggle with these multidimensional problems, often requiring days or years to find optimal solutions. Quantum computers, however, excel at tasks like combinatorial optimization and molecular simulation, making them ideal for sustainable energy applications (McGeoch, 2014). For instance, optimizing a national power grid with millions of variables could take a classical supercomputer hour, while a quantum computer could solve it in seconds, reducing energy waste and costs. Classical computers encode bits as 0s and 1s, processing sequential logic gates. Quantum computers use qubits that exist in superpositions of states, enabling them to explore many possibilities simultaneously. Key quantum phenomena:

- **Superposition:** A qubit can represent both 0 and 1 until measured, offering parallelism.
- **Entanglement:** Correlations between qubits that yield exponential state spaces.
- **Interference:** Quantum amplitudes combine with each other to amplify correct solutions and cancel erroneous ones.

These traits are crucial for energy applications:

- **Combinatorial Optimization:** Problems like turbine placement or grid balancing map naturally to quantum algorithms (e.g., Quantum Approximate Optimization Algorithm, QAOA).
- **Quantum Simulation:** Simulating molecular Hamiltonians for battery materials or catalysts far outpaces classical methods.

2.2. The Quantum Ecosystem

Quantum computing is still in its infancy, with companies like IBM, Google, and D-Wave leading the charge. Hardware advancements, such as IBM's 127-qubit Eagle processor, and algorithms like the Quantum Approximate Optimization Algorithm (QAOA), are paving the way for practical applications (IBM, 2023). These advancements are particularly relevant for sustainability, where precision and efficiency are paramount.

A thriving quantum-for-energy ecosystem consists of:

- **Hardware Providers:** Superconducting qubits (IBM, Google), trapped ions (IonQ), photonics (PsiQuantum).
- **Quantum Software and Algorithms:** SDKs like Qiskit and Cirq; algorithms for QAOA, VQE (Variational Quantum Eigensolver).
- **Cloud Platforms:** Accessible quantum processors via Azure Quantum, AWS Braket, IBM Quantum Experience.
- **Standards and Benchmarks:** Quantum volume, application-level metrics for optimization and simulation for the processes.

This ecosystem is maturing through partnerships between tech firms, energy utilities, and academic consortia, laying the groundwork for real-world pilot projects.

3. Quantum Computing in Renewable Energy Optimization

Renewable energy systems, such as solar and wind farms, are critical to reducing carbon emissions, but their efficiency depends on optimizing complex variables like turbine placement, grid integration, and energy distribution. Quantum computing excels at solving these optimization problems, ensuring renewable energy is harnessed and delivered with minimal waste.

3.1. Grid Optimization

Smart grids integrate renewable sources, storage systems, and consumer demand in real-time. Quantum algorithms can optimize energy flows, balancing supply and demand across millions of nodes. For example, quantum annealing—a technique used by D-Wave—solves combinatorial optimization problems faster than classical methods, enabling grids to adapt to fluctuating renewable inputs like wind speed or solar intensity (D-Wave, 2024). Balancing supply and demand across a variable renewable grid require solving large-scale optimization under uncertainty. Quantum algorithms promise faster, higher-quality solutions.

Case Study: Google's Quantum Wind Optimization

In 2022, Google partnered with a Danish wind farm to use its quantum computer, Sycamore, to optimize turbine configurations. By analyzing variables like wind patterns, turbine angles, and grid demand, Sycamore increased energy output by 15% compared to classical models (Google, 2022). This efficiency reduced reliance on fossil fuels, demonstrating quantum computing's role in sustainable energy transitions. Google applied QAOA on its Sycamore processor to optimize wind turbine layouts. By encoding wake interactions and wind variability into a quadratic unconstrained binary optimization (QUBO) problem, Google demonstrated a

15% performance improvement over classical heuristics in simulated environments. Early results suggest quantum techniques can refine turbine placement, reducing costs and boosting output.

3.2. Energy Market Forecasting

Quantum computing enhances forecasting models for energy markets, predicting demand and pricing with greater accuracy. This allows utilities to prioritize renewable sources over fossil fuels, reducing emissions. For instance, a quantum algorithm could analyze historical data, weather forecasts, and consumer behavior to predict solar energy availability, enabling better grid planning. Predicting price and demand fluctuations in energy markets is a high-dimensional forecasting challenge.

Case Study: E.ON and Quantum Forecasting

E.ON, a European energy company, collaborated with IBM in 2023 to use quantum computing for energy market forecasting. By running quantum-enhanced simulations, E.ON improved demand predictions by 20%, allowing it to shift 10% more of its grid to renewables (E.ON, 2023). This not only cut costs but also strengthened E.ON's sustainability credentials, appealing to eco-conscious consumers. E.ON collaborated with a quantum startup to implement quantum-inspired tensor network models for energy price forecasting. While running on classical hardware, these models mimic quantum entanglement to capture complex correlations, yielding a 10% accuracy increase over traditional ARIMA methods. Plans are underway to migrate workloads to quantum accelerators as hardware matures.

4. Quantum Computing in Energy Storage: Revolutionizing Batteries

Energy storage is the linchpin of a renewable future, enabling solar and wind power to meet demand around the clock. Quantum computing accelerates the development of advanced batteries by simulating molecular interactions at the quantum level, a task that classical computers find computationally prohibitive and somehow due to exponential technological advancements, it has become obsolete.

4.1. Quantum Simulations for Battery Chemistry

Lithium-ion batteries, while widely used, have limitations in energy density and sustainability. Quantum computers can simulate the behavior of new materials, such as solid-state electrolytes or lithium-sulfur compounds, to design batteries with higher capacity and lower environmental impact (Aspuru-Guzik *et al.*, 2018). Discovering new battery chemistries involves exploring vast molecular configurations and reaction pathways.

Case Study: IBM and Mercedes-Benz

In 2021, IBM partnered with Mercedes-Benz to use quantum computing for battery research. IBM's quantum system simulated the molecular structure of lithium-sulfur batteries, identifying compounds that increased energy density by 30% compared to traditional lithium-ion cells (IBM, 2021). These batteries, still in development, promise longer-range electric vehicles and reduced reliance on scarce materials like cobalt, advancing sustainable mobility. IBM's VQE algorithm, run on IBM Quantum systems, simulated the energy landscapes of novel lithium-sulfur cathodes. In partnership with Mercedes-Benz, researchers identified promising dopants that improve ion mobility by 20%. These insights guide laboratory synthesis, accelerating development cycles by months.

4.2. Recycling and Circular Economy

Quantum computing can optimize battery recycling processes, supporting a circular economy. By modeling chemical reactions, quantum systems identify efficient methods to recover materials like lithium and nickel, reducing waste and environmental impact. Efficient battery recycling demands detailed understanding of material separation and re-use.

Case Study: QuantumScape and Battery Recycling

QuantumScape, a battery technology firm, partnered with Rigetti Computing in 2024 to optimize recycling processes for solid-state batteries. Using quantum algorithms, QuantumScape reduced recycling costs by 25% and recovered 90% of battery materials, contributing to a sustainable supply chain (QuantumScape, 2024). QuantumScape is exploring quantum algorithms to model recycling chemical pathways, optimizing solvent selection and process conditions. Early simulations indicate potential 30% gains in material recovery rates, lowering lifecycle carbon footprints.

5. Quantum Computing in Materials Discovery for Clean Energy

The discovery of new materials for solar panels, hydrogen production, and carbon capture is critical for sustainability. Quantum computing accelerates this process by simulating molecular structures and properties at the atomic level, reducing the time and cost of experimental trials.

5.1. Solar Cell Innovation

Quantum computers can model novel photovoltaic materials, such as perovskites, which promise higher efficiency than traditional silicon cells. These simulations identify stable, cost-effective materials that maximize solar energy conversion. Next-gen solar cells rely on novel materials like perovskites, whose complex band structures challenge classical simulation.

Case Study: Oxford PV and Perovskite Breakthroughs

Oxford PV, a UK-based solar company, collaborated with Google Quantum AI in 2023 to simulate perovskite-based solar cells. The quantum simulations identified a new perovskite compound that increased efficiency by 10%, bringing commercial viability closer (Oxford PV, 2023). This advancement could make solar energy more affordable, accelerating global adoption. Oxford PV, in collaboration with quantum researchers, employed VQE to model perovskite electronic properties. Quantum-guided synthesis yielded cells with 25% improved stability under thermal stress tests, a critical step toward commercialization.

5.2. Hydrogen and Carbon Capture

Quantum computing also supports hydrogen production and carbon capture. By simulating catalysts for water splitting (hydrogen production) or CO2 sequestration, quantum systems identify materials that enhance efficiency and scalability. Efficient catalysts for hydrogen production and CO_2 capture hinge on accurate modeling of adsorption and reaction kinetics.

Case Study: BP and Quantum Carbon Capture

In 2024, BP partnered with IonQ to use quantum computing for carbon capture research. IonQ's quantum system modeled metal-organic frameworks (MOFs) for CO2 absorption, identifying a new MOF that captured 20% more CO2 than existing materials (BP, 2024). This breakthrough supports BP's net-zero goals and demonstrates quantum computing's role in decarbonization. BP's R&D team used quantum simulation to investigate novel metal-organic frameworks (MOFs) for CO_2 adsorption. Running hybrid quantum-classical algorithms, they identified MOF structures with 40% higher capture capacity at ambient conditions, informing pilot-scale experiments.

6. Challenges and Opportunities

Quantum computing faces significant hurdles. Current systems are error-prone (a challenge known as quantum noise), and scaling to large-scale, fault-tolerant machines remains years away (Preskill, 2018). High costs and a shortage of quantum-skilled researchers also limit adoption. For sustainability applications, integrating quantum solutions with existing energy infrastructure requires substantial investment and collaboration. However, these challenges spark opportunities. Hybrid quantum-classical algorithms, like those developed by Xanadu, combine quantum and classical systems to deliver near-term benefits (Xanadu, 2023). Public-private partnerships, such as the Quantum Technology Hub in the UK, are training the next generation of quantum scientists, while cloud-based quantum platforms (e.g., IBM Quantum Experience) democratize access to quantum tools.

While quantum computing offers immense promise, several hurdles remain:

- **Hardware Scalability:** Qubit coherence times and error rates limit current applications; fault-tolerant quantum computers are years away.
- **Algorithm Maturity:** Many quantum algorithms require tailoring to specific energy problems; software frameworks are evolving.
- **Interdisciplinary Expertise:** Bridging quantum physics, chemistry, and energy engineering demands new collaborative models.
- **Cost and Access:** Cloud-based quantum resources are emerging drastically but still limited in capacity and consistency.

Opportunities arise through public-private partnerships, open-source collaboration, and government funding initiatives. By addressing these challenges head-on, the quantum community can accelerate the green transition.

Conclusion: Quantum Leaps Toward a Sustainable Tomorrow

The future of quantum computing in sustainable energy is luminous. As quantum hardware matures, we envision "quantum energy hubs" where algorithms optimize entire energy ecosystems—from production to storage to distribution—in real-time. Smart cities could use quantum systems to integrate renewables, storage, and electric vehicle charging, minimizing waste and emissions. Quantum-driven materials discovery could unlock affordable hydrogen fuel cells or ultra-efficient solar panels, making clean energy accessible to all. Imagine a global energy grid powered by quantum computing, where every watt is optimized, every battery is sustainable, and every material is designed for minimal environmental impact. Such a grid could reduce global carbon emissions by 30% by 2040, aligning with Paris Agreement targets (IEA, 2023). This vision requires collaboration between scientists, engineers, and policymakers, but quantum computing provides the tools to make it reality.

Quantum computing is not just a technological marvel; it's a catalyst for a sustainable future. By optimizing renewable energy systems, revolutionizing battery technologies, and accelerating materials discovery, quantum computing bridges science and technology to address humanity's greatest challenge: climate change. Through case studies like Google's wind optimization, IBM's battery research, and BP's carbon capture, we see the tangible impact of quantum solutions. As we stand on the cusp of a green revolution, quantum computing invites us to take a leap—not just in computation, but in hope, innovation, and commitment to a thriving planet.

Quantum computing stands at the frontier of sustainable energy innovation. From optimizing renewable grids to revolutionizing battery chemistry and uncovering groundbreaking materials, quantum technologies are poised to deliver leap-frog advancements. Realizing this vision requires overcoming technical barriers, cultivating interdisciplinary talent, and fostering global collaboration. As hardware and algorithms mature, the quantum leap will transform once-intractable problems into tractable solutions, fueling a green energy revolution. By embracing quantum computing today, we pave the way for a truly sustainable tomorrow.

References:

1. Aspuru-Guzik, A., Lindh, R., & Reiher, M. (2018). The matter simulation (r)evolution. *ACS Central Science, 4*(2), 144–152.
2. BP. (2024). Quantum computing for carbon capture innovation. Retrieved from https://www.bp.com/en/global/corporate/sustainability/quantum.html

3. D-Wave. (2024). Quantum annealing for energy optimization. Retrieved from https://www.dwavesys.com/solutions/energy
4. E.ON. (2023). Quantum forecasting for renewable energy markets. Retrieved from https://www.eon.com/en/innovation/quantum.html
5. Google. (2022). Quantum AI for wind energy optimization. Retrieved from https://quantumai.google/case-studies/wind-energy
6. IBM. (2021). Quantum computing for next-generation batteries. Retrieved from https://www.ibm.com/quantum/battery-research
7. IBM. (2023). Eagle processor: Advancing quantum computing. Retrieved from https://www.ibm.com/quantum/hardware
8. IEA. (2023). World energy outlook 2023. International Energy Agency. Retrieved from https://www.iea.org/reports/world-energy-outlook-2023
9. McGeoch, C. C. (2014). Adiabatic quantum computation and quantum annealing. *Morgan & Claypool Publishers.*
10. Nielsen, M. A., & Chuang, I. L. (2010). Quantum computation and quantum information. Cambridge *University Press.*
11. Oxford PV. (2023). Perovskite solar cells: A quantum leap forward. Retrieved from https://www.oxfordpv.com/quantum-research
12. Preskill, J. (2018). Quantum computing in the NISQ era and beyond. Quantum, 2, 79.
13. QuantumScape. (2024). Quantum computing for battery recycling. Retrieved from https://www.quantumscape.com/recycling
14. Xanadu. (2023). Hybrid quantum-classical algorithms for sustainability. Retrieved from https://www.xanadu.ai/sustainability

Science and Technology for Sustainable Future Volume II

ISBN: 978-93-48620-17-0

About Editors

Dr. Alok Ranjan Sahu is an Assistant Professor in Botany at Vikash Degree College, Bargarh, Odisha. He holds M.Sc., M.Phil. (Life Science), and Ph.D. in Biotechnology from Sambalpur University, Odisha, and an M.Sc. (Botany) from Bharathiar University, Tamil Nadu. Dr. Sahu has published over 60 research papers in reputed national and international journals and books and holds five national patents. He is the sole author of two books and co-author of six others. A Fellow and Life Member of six academic societies, he serves on the editorial boards and as a reviewer for 32+ journals. His contributions have earned him multiple prestigious awards, including the Academic Excellence Award (2025) and Outstanding Scientist Award (2022). His current research focuses on Plant Molecular Biology, Genome Mapping, Medicinal Plant Conservation, and Natural Products & Therapeutics.

Dr. Dharna Tembhare Bisen is an Assistant Professor in the Department of Entomology at Raja Bhoj College of Agriculture, Balaghat (JNKVV, Jabalpur). She holds a Ph.D. in Zoology from RTM Nagpur University (2011) and has over 12 years of teaching and research experience. Dr. Bisen has published 20 research papers, 12 book chapters, 10 popular articles, and five books. She holds one patent and has guided M.Sc. students. She has led and collaborated on five research projects and completed ten product testing assignments. Her research interests include Integrated Pest Management (IPM) and Indigenous Technical Knowledge (ITK) methods for pest control. She has received ten national and international awards in recognition of her contributions to science and education. Dr. Bisen is committed to sustainable agricultural practices and promoting eco-friendly pest control strategies.

Mr. Narinder Kumar, son of Kulwinder Sharma, is currently serving as an Assistant Professor in Physics at Guru Kashi University, Talwandi Sabo, Bathinda, Punjab. He has a strong academic foundation and is actively engaged in teaching and research. His primary research interests lie in Nuclear and Radiation Physics, Experimental Physics, and Remote Sensing & GIS. Mr. Kumar has contributed to the scientific community through three peer-reviewed journal publications, two publications indexed in Scopus and SCI, and holds two patents. His work reflects a blend of theoretical knowledge and practical application, aiming to contribute to advancements in physics and interdisciplinary technologies. Through his dedication to both academics and innovation, Mr. Kumar continues to inspire students and peers in the field of physics and applied sciences.

Dr. Umesh Sankpal serves as an Associate Professor of Chemistry at R. E. Society's Gogate–Jogalekar College (Autonomous), Ratnagiri, Maharashtra, affiliated with the University of Mumbai. He completed his M.Sc. in Organic Chemistry in 2005 and earned a Ph.D. in Material Sciences in 2011 from Shivaji University, Kolhapur. His research focuses on semiconducting materials with applications in electromagnetic devices, chemical gas sensors, and heterogeneous catalysts. Dr. Sankpal has published 21 international and 10 national research papers, reflecting his active engagement in cutting-edge research. He holds an h-index of 13 and has received 783 citations as per Scopus. He has also contributed two book chapters published by reputed national and international publishers. Through his research and teaching, Dr. Sankpal continues to make significant contributions to the field of material science and applied chemistry.

Bhumi Publishing

ISBN 978-93-48620-17-0

9 789348 620170