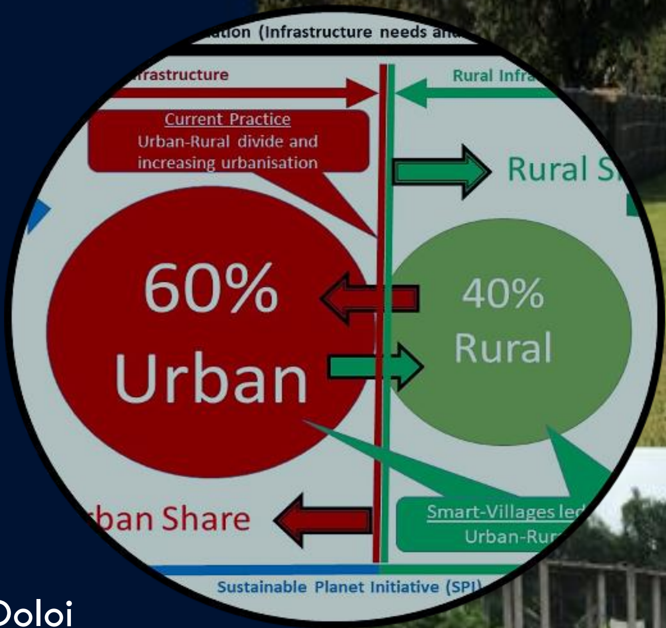
# Proceedings of
# The 8th International Conference on Smart Villages and Rural Development
# COSVARD 2025

*15-16 December 2025*
*Hybrid Mode*

*In-person location:*
*SASTRA Deemed University*
*Thanjavur, Tamil Nadu*
*India 613401*




Editors:

A/Prof Hemanta Doloi
Prof Sujatha E Ramani
Prof Suribabu C. R.
Dr Santhosh Loganathan

Smart Villages Lab
Culture • Construction • Capacity • Community

The University of Melbourne
Victoria 3010, Australia

The 8th International Conference on Smart Villages and Rural Development (COSVARD 2025) hosted by the Smart Villages Lab (SVL) of the Faculty of Architecture, Building and Planning of the University of Melbourne in collaboration with the SASTRA Deemed University, Thanjavur, Tamil Nadu, India.

Date: 15-16 December 2025
In-person venue: SASTRA Deemed University, Thanjavur, Tamil Nadu, India (in Hybrid Mode)

***Publication Data***
This Proceedings contains the double-blind peer-reviewed research papers presented at the COSVARD 2024 Conference, hosted by the Smart Villages Lab (SVL) of the Faculty of Architecture, Building and Planning of the University of Melbourne, in collaboration with the SASTRA Deemed University, Thanjavur, Tamil Nadu, India, held in a Hybrid Model on 15-16 December 2025.

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***Conference Chairman and Editors***
Associate Prof Hemanta Doloi (Chair)
Editor-in-Chief (COSVARD 2025), Smart Villages Lab (SVL), The University of Melbourne
Prof Sujatha E Ramani (Co-Chair), Co-Editor (COSVARD 2025), SASTRA Deemed University, India
Prof Suribabu C.R. (Co-Chair), Co-Editor (COSVARD 2025), SASTRA Deemed University, India
Dr Santhosh Loganathan (Co-Chair), Co-Editor (COSVARD 2025), NIT Trichy, Trichy, India

***Publisher***
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## Publication Note

The *Proceedings of the International Conference on Smart Villages and Rural Development (COSVARD 2025)* comprise peer-reviewed papers accepted for presentation at COSVARD 2025and selected for publication in the official COSVARD Proceedings series (**ISSN 2982-0731 [Online]; ISSN 2982-0723 [Print]**), Volume 8, Issue No. 1, 2025

A total of **six papers** are included in this volume. These papers are identified in **green text** in the COSVARD 2025 Conference Schedule.

A separate selection of papers presented at COSVARD 2025 has been selected for publication by Springer Nature in the *Lecture Notes in Civil Engineering* series. These contributions are identified with an **asterisk (*)** in the Conference Schedule. To ensure clear and transparent publication records and to avoid duplicate publication, papers included in the Springer Nature volume are **not reproduced in the present COSVARD Proceedings**.

The Springer Nature publication is:

**Smart Villages and Sustainable Rural Transformation: Integrating Design, Technology, and Social Innovation**

***Bibliographic Information***

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**Length:** 290 pages
**Subject:** Technology & Engineering – Civil Engineering

Accordingly, the papers contained in the present volume represent **only those contributions formally published through the COSVARD Proceedings series**. Papers selected for publication through Springer Nature constitute a separate publication stream and should be cited exclusively from their respective Springer Nature publication, using the relevant bibliographic details and DOI where available.

This distinction is intended to maintain the integrity of the COSVARD publication record, ensure appropriate attribution and indexing, and avoid any duplication between the COSVARD Proceedings and the Springer Nature volume.

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*W107- Construction in Developing Countries*

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# The 8th International Conference on Smart Villages and Rural Development (COSVARD 2025)

Hybrid Mode

**(In-person Venue: Seminar Hall 2 - ASK 410, SASTRA Deemed University, Thanjavur, Tamil Nadu, India)**

**15-16 December 2025**

**University of Melbourne Organising committee:**
A/Prof Hemanta Doloi (Chair)
Prof Robert Crawford
Dr Hannah Robertson
Dr Gao Shang

**SASTRA Deemed University Local Support Committee**
Prof Suribabu C.R (Co-Chair)
Prof Sujatha E Ramani (Co-Chair)
Dr Santhosh Loganathan (Co-Chair) – NIT Trichy

**Key Affiliating Partners**
Indian Institute of Technology, Guwahati
National Institute of Technology, Trichy
Smart Cities Research Institute (SCRI) - Swinburne University of Technology, Australia
Indian Institute of Technology, Delhi
Indian Institute of Technology, Tirupati
Indian Institute of Technology, Madras

**Topic**: COSVARD 2025
**Time**: 15-16 December
9:00am (Indian Standard Time, IST)
2:30pm (Australian Eastern Daylight Time)

Registration Link:
https://unimelb.zoom.us/webinar/register/WN_TTwq-aFFSpeUxvlorrs6OA
(Or Scan the QR to visit the link)

After registering, you will receive a confirmation email containing information about joining the webinar.

**Webinar ID**: 882 3316 1815
**Password**: 732481 (if prompted)

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# The 8th International Conference on Smart Villages and Rural Development (COSVARD 2025)

## Hybrid Mode
## 15-16 December 2025

With over 40% of the world's population now living in rural areas, there is global interest in research associated with the creation of "Smart Villages" to address the ever-growing urban-rural divide. Smart Village research being undertaken in the Faculty of Architecture, Building and Planning at the University of Melbourne is exploring rural community development, practices and relevant policies with a focus on community-centric planning of affordable housing, infrastructure, sustainable development and growth, community empowerment and other issues related to the creation of Smart Villages.

**About the conference**
This will be a peer-reviewed conference with a scientific committee comprising global leaders and experts. Full papers will be subject to a double-blind review before acceptance.

**Themes**
Conference themes include, but are not limited to:

**Rural Housing** - Housing affordability, low-cost housing, local materials and resources

**Rural Infrastructure** - Roads and other forms of infrastructure, access to education and health

**Rural Economy** – Micro and community-led finance, income generation, farming & crops supports

**Sustainability** - Environmental, Social, and Economic Sustainability and resilience

**Smart Governance** - ICT and data- applications, alternative forms of governance and other relevant topics

**Circular Economy** - Framework for local manufacturing, local production, local consumption

**Social Procurement, Social Value and Value-for-Money** - Community-specific social benefits

**Rural Enterprises and Rural Entrepreneurship** – Entrepreneurial capability and capacity to leverage

**Rural Culture and Experience** – Appreciation, preservation, characterisation rural cultures and values

**Climate Change, Global Warming and Role of Rural Development (targeting the 40%)** - Alternative, value-based, context-specific development models targeting the 40% global population who still live in rural but relatively in low-carbon footprints.

**Smart and Sustainable Infrastructure for Rural Areas** - Includes research on Modern Housing Solutions for Rural Communities, Developing Efficient Transportation Networks in Villages, Water Supply and Sanitation: Urban Standards in Rural Settings, and Building Climate-Resilient Rural Infrastructure**.**

**Digital Connectivity and Technology Access** - Include research on the Role of Technology in Delivering Urban-Like Services to Villages, E-Governance and Digital Public Services for Rural Communities, Cost-effective digital solutions for water supply, sewage and solid waste management.

**Low Carbon and Lean Construction** - Low-carbon footprints and low-waste, low-cost construction practices

**Location**
The Conference will be held in-person and in Webinar formats on 15 – 16 Dec, *2025 starting at 9:00am (Indian Standard Time, IST). For registration, visit*
https://unimelb.zoom.us/webinar/register/WN_TTwq-aFFSpeUxvIorrs6OA

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**15-16 December 2025**

## Keynote Speakers

1. **Professor Mohan M Kumaraswamy,** *Editor-in-Chief (Emerald Journal of the Built Environment Project and Asset Management – BEPAM)*
   **Topic: "Rural-Urban synergies and Integrated Regenerative Built Environments"**

2. **Professor George Ofori**, *Sustainability Lead for LSBU Group, London South Bank University, London, UK*
   **Topic: "Building the Body of Knowledge in Project Management for Developing Countries: context of smart villages"**

3. **Professor V.K. Vijay,** *National Coordinator, IREDA Chair Professor, Country-Head (Unnat Bharat Abhiyan) (IIT Delhi)*
   **Topic: "Unnat Bharat Abhiyan – the Program of the Education Ministry, GoI, to revolutionise rural development by utilising the knowledge and experience of higher education institutions"**

4. **Prof Ani Raiden,** *Nottingham Trent University*
   **Topic: "Topic: Co-Creation as a Framework for Social Value in Smart Villages – Critical Reflections on the Approach, Challenges and Opportunities"**

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## Scientific committee

- Professor Craig Langston, Bond University, Australia
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- Professor Anthony Mills, Deakin University, Australia
- Professor Bishwajit Bhattacharjee, Indian Institute of Technology, Delhi, India
- Dr Yoshiki Higuchi, Nippon Institute of Technology, Japan
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- Dr B. Mahesh, IIT Madras, Chennai, India
- Ms Dwijomala Hanjabam, Mizoram University, India
- Mr Abdullatif Abdallah (Smart Villages Lab), The University of Melbourne
- Dr Luisa Lombardo, UniPa, Italy
- Dr Sujatha E Ramani, SASTRA University, Thanjavur, India
- Prof Neelakantan T R, SASTRA University, Thanjavur, India
- Dr Santhosh Loganathan, NIT Trichy, India

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# The 8th International Conference on Smart Villages and Rural Development (COSVARD 2025)

## Hybrid Mode
## 15-16 December 2025

## Agenda for Opening Ceremony and Inauguration (In-Person)
## Day 1 – Monday 15 December 2025

***Seminar Hall 2 - ASK 410, SASTRA Deemed University***

**9:30am– 11:30am (IST^) or 3:00pm – 5:00pm (AEDT#)**

*^Indian Standard Time (IST), #Australian Eastern Daylight Time (AEDT)*

| **Anchored by: Dr. Vidya R** | |
|---|---|
| **9:30am (IST)**<br>**3:00pm (AEDT)** | **The official opening of COSVARD 2025, Welcome Guests, Felicitation of the Guests** |
| **9:35am (IST)**<br>**3.05pm (AEDT)** | **Opening COSVARD 2025 and Welcome by Local Hosts, SASTRA Deemed University** |
| **9:40am (IST)**<br>**3:10pm (AEDT)** | **Opening Speech**<br>**A/Prof Hemanta Doloi** *(Chair, COSVARD 2025),The University of Melbourne* |
| **9:45am (IST)***<br>**3:15pm (AEDT)**<br>** may need adjustment* | **Inaugural Speech**<br>**Prof Panchanatham, Vice Chancellor,** *Gandhigram Rural University, Gandhigram, Tamil Nadu, India* |
| **10:10am (IST)**<br>**3:40pm (AEDT)** | **Special Guest**<br>**Prof Muthukkumaran, Head, Dept of Civil Engineering,** ***NIT Trichy*** |
| **10:20am (IST)**<br>**3:50pm (AEDT)** | **Address by Prof. Neelakantan TR,** *SASTRA Deemed University* |
| **10:30am (IST)**<br>**4:00pm (AEDT)** | **Address by Prof. Suribabu CR,** *SASTRA Deemed University* |
| **10:40am (IST)**<br>**4:10pm (AEDT)** | **Address by Prof. Badrinath R,** *SASTRA Deemed University* |
| **10:50am (IST)**<br>**4:20pm (AEDT)** | **Address by Prof Robert Crawford,** *The University of Melbourne* |
| **11:00am (IST)**<br>**4:30pm (AEDT)** | **Address by Dr Hannah Robertson,** *The University of Melbourne* |
| **11:10am (IST)**<br>**4:40pm (AEDT)** | **Address by Dr Gao Shang,** *The University of Melbourne* |
| **11:20am (IST)**<br>**4:50pm (AEDT)** | **Vote of Thanks – by Prof. Sujatha E Ramani** |
| | |
| **High Tea 11:30am - 12:00pm (IST)**<br>**5:00pm – 5:30pm (AEDT)** | |
| **Technical Session starts at 12:15pm (IST)**<br>**5:45pm (AEDT)** | |

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## Technical Session
## Day 1 - Monday 15 December 2025

| | | |
|---|---|---|
| **12:15pm (IST)**<br>**5:45pm (AEDT)** | **Keynote 1: Professor Mohan M Kumaraswamy**<br>*Editor-in-Chief (Emerald Journal of the Built Environment Project and Asset Management – BEPAM); Honorary Professor, The University of Hong Kong, Hong Kong Honorary Professor, University of Moratuwa, Sri Lanka*<br>**Topic: Rural-Urban synergies and Integrated Regenerative Built Environments**<br>***Chair: Prof. Suribabu CR*** | |
| | **Technical Papers** | |
| **12:45 (IST)**<br>**6:15pm (AEDT)** | **Session 1: Conceptual Frameworks and Global Perspectives on Smart Villages** | |
| | **Chair: Dr. Subramanyam B** | **Authors** |
| ***Paper 3**<br>*(15 mins)* | Smart Villages and Village Road Safety in India | Ravindra Kumar[1], Subhash Chand[1], S. Padma[2], V A Bharat Kumar Anna[3], Afeef Hashmi[4]<br>*[1] Chief Scientist, Prof AcSIR, CSIR-Central Road Research Institute, New Delhi*<br>*[2] Senior Principal Scientist, TPE , Prof AcSIR CSIR-Central Road Research Institute New Delhi*<br>*[3] Assistant Professor, Department of Civil Engineering, Vignan's Foundation for Science, Technology and Research, Vadlamudi, Guntur, India*<br>*[4]Research Intern CRRI, CSIR-Central Road Research Institute New Delhi* |
| ****Paper 4***<br>*(15 mins)* | Tools for the enhancement, rehabilitation and valorisation of Smart Villages in Sicily | Luisa Lombardo and Tiziana Campisi<br>*Department of Architecture, University of Palermo* |
| **Paper 5**<br>***(15 mins)*** | Significance of Smart Villages and Rural Development in the present scenario | Girish Chandra Gandhi[1], Payal Mehta[2], Ankit Sodha[3]<br>*[1]Indus University Ahmedabad*<br>*[2]Indus University* |
| ***Paper 11**<br>*(15 mins)* | Towards Sustainable Rural Transformation: A Case Study of Smart Village Development in Odanthurai, Tamil Nadu | Akilandeswari P, Hari Priya R, Subramanyam B<br>*SASTRA Deemed University* |
| ***Paper 22**<br>*(15 mins)* | Establishing Economically Viable Smart Villages: A Case of Nyandeni Smart Village Pilot Project in South Africa | Mziwoxolo Sirayi[1], Mcebisi Mabuza[2], Sibusiso Ndlangamandla[3]<br>*[1]Faculty of Management, Commerce, and Law, University of Venda, Thohoyandou, 0950*<br>*[2]Department of Plant and Soil Science, University of Pretoria, Hatfield, 0083*<br>*[3]Department of English, University of South Africa, Muckleneuk, Pretoria, 0003* |
| **2:00pm (IST)**<br>**7:00pm (AEDT)** | **Lunch (2:00pm-3:30pm)** | |

| | | |
|---|---|---|
| 3:30pm (IST)<br>9:00pm (AEDT) | **Keynote 2: Professor George Ofori**<br>*Sustainability Lead for LSBU Group, London South Bank University, London, UK*<br>**Topic: Building the Body of Knowledge in Project Management for Developing Countries: context of smart villages**<br>***Chair: Prof. Sujatha E Ramani*** | |
| **4:00pm (IST)<br>9:30pm (AEDT)** | **Session 2: Conceptual Frameworks and Global Perspectives on Smart Villages**<br>Chair: Dr. Selvakumar R | |
| ***Paper 14**<br>(*15 mins*) | Tracking built-up land dynamics in Cauvery basin districts of Tamil Nadu: Geospatial-based insights for rural sustainability | N Rishibala , S Rupika Veni Durga , Vasu Sathyakumar , R Selvakumar<br>*SASTRA Deemed University* |
| ***Paper 15**<br>(*15 mins*) | Nature-Based solutions for smart urban and rural transition: Green integration strategies for climate change | Simona Colajanni , Luisa Lombardo , Marco Bellomo , Tiziana Campisi<br>*University of Palermo, Italy* |
| ***Paper 28**<br>(*15 mins*) | Collective bioclimatic spaces in the Madonie inner area (Sicily) | Luisa Cerami , Tiziana Campisi<br>*University of Palermo, Italy* |
| **Paper 29**<br>(*15 mins*) | Sustainability Literacy and Stakeholder Engagement: Delivering Affordable and Sustainable Social Housing in the UK | Tharaki Hettiarachchi[1], Hemanta Doloi[2], Jamal Alabid[3]<br>[1]*Peterborough College, United Kingdom.*<br>[2]*The University of Melbourne, Australia.*<br>[3]*Heriot-Watt University, United Kingdom* |
| **Paper 41**<br>(*15 mins*) | Advancing social sustainability in infrastructure design: a review of indicators for stakeholder acceptance and social value | Fahmi Firdaus Alrizal , Mohamad Arif Rohman , I Putu Artama Wiguna<br>*Institut Teknologi Sepuluh Nopember* |
| **5:15pm (IST)<br>10:45pm (AEDT)** | **Tea Break (5:15pm – 5:45pm)** | |
| ***Paper 9**<br>(*15 mins*) | Integrating Closed-Loop Systems for Efficient and Sustainable Waste Management | Hari Priya R, Akilandeswari P, Subramanyam B<br>*SASTRA Deemed University* |
| ***Paper 13**<br>(*15 mins*) | Smart and sustainable self-healing concrete incorporating production residues and natural fibers | Elakkiya K , Sumathi A<br>*SASTRA Deemed University* |
| ***Paper 24**<br>(*15 mins*) | Reusing Structural Steel for Resilient and Sustainable Rural Buildings | Giulio Basileo<br>*Università degli Studi dell'Aquila, Italy* |
| **6:30pm (IST)<br>12:00am (AEDT)** | **End of Day 1** | |

# The 8th International Conference on Smart Villages and Rural Development (COSVARD 2025)

**Hybrid Mode**

**15-16 December 2025**

## Technical Session
## Day 2 - Tuesday 16 December 2025

| | | |
|---|---|---|
| 9:30am (IST)<br>3:00pm(AEDT) | **Keynote 3: Prof V.K. Vijay**<br>*National Coordinator, IREDA Chair Professor, Country-Head (Unnat Bharat Abhiyan) (IIT Delhi)*<br>**Topic: Unnat Bharat Abhiyan – the Program of the Education Ministry, GoI, to revolutionise rural development by utilising the knowledge and experience of higher education institutions**<br>***Chair: Dr. Neeelakantan TR*** | |
| 10.00am(IST)<br>3:30pm (AEDT) | **Session 3: Circular and Decentralised Infrastructure System**<br>**Chair: Dr. Vidya R** | |
| ***Paper 33**<br>(*15 mins*) | An experimental study on light weight foam concrete | Nishita Barman[1], Nayanmoni Chetia[2]<br>[1] *MTech Student, Jorhat Engineering College*<br>[2]*Professor, Civil Engineering Department, Jorhat Engineering College.* |
| ***Paper 34**<br>(*15 mins*) | A Prototype of Sustainable Rural Housing through Local Materials | Venkata Subramanian C , Muthu D , Vidya R , Sharmila P , Vivek S.S<br>*SASTRA Deemed University* |
| 10.30am(IST)<br>4:00pm (AEDT) | **Tea Break (10:30am – 11:00am)** | |
| ***Paper 35**<br>(*15 mins*) | Decentralized Greywater Management in Rural Homes Using a Passive Syphon System with Coagulation and Filtration | Ramprasad Chandrasekaran , Harshini Arivalagan Jayachitra , Kaaraneeswaran Karthikeyan , Suvethasri Amaresan<br>*SASTRA Deemed University* |
| ***Paper 36**<br>(*15 mins*) | Influence of Nano Silica on Sustainable development of High Performance Concrete | Jaishankar P, Venkatasubramanian C, Muthu D, Venkatesh P<br>*SASTRA Deemed University* |
| ***Paper 38**<br>(*15 mins*) | Effect of blended micro and macro size fibers on mechanical properties of reactive powder concrete using mineral admixture | Kalaiselvan L.S, Elavarasi D<br>*SASTRA Deemed University* |
| ***Paper 40**<br>(*15 mins*) | Sustainable Rubberized Light Weight Engineered Geopolymer Composites – A Review | Jaya sheela V , Ajay Prabhu R, Bhuvaneshwari P<br>*SASTRA Deemed University* |
| **Paper 27**<br>(*15 mins*) | Bio-based insulation materials for rural housing renewal: challenges and opportunities | Zanhai Huang, Lulu Jiang, Fernanda Speciale, Laura Elisabetta Malighetti<br>*Politecnico di Milano, Italy* |
| **Paper 30**<br>(*15 mins*) | Fabrication and characterization of natural fibre based hybrid composites for smart village innovations | Menonjyoti Kalita, Pradip Baishya<br>*Assam Engineering College, India* |
| 12.30pm (IST)<br>6:00pm (AEDT) | **Lunch Break (12:30pm – 2:00pm)** | |

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## Hybrid Mode
## 15-16 December 2025

| | | |
|---|---|---|
| **2:00pm(IST)**<br>**7:30pm (AEDT)** | **Keynote 4: Prof Ani Raiden,** *Associate Professor in Responsible Management*<br>*Nottingham Trent University, United Kingdom*<br>**Topic: Co-Creation as a Framework for Social Value in Smart Villages – Critical Reflections on the Approach, Challenges and Opportunities**<br>***Chair: Dr. Hemanta Doloi*** | |
| **2:30pm(IST)**<br>**8:00pm (AEDT)** | **Session 4: Circular and Decentralised Infrastructure System**<br>**Chair: Dr. Vivek SS** | |
| ***Paper 26**<br>*(15 mins)* | Correlating strength with acoustic and visual characteristics for non-destructive assessment of red bricks | Sunirmal Chattopadhyay , Shubhadeep Mukherjee , Astha Sharma , Plabon Kakati<br>*Assam Engineering College, India* |
| ***Paper 32**<br>*(15 mins)* | A Study on the Flexural Performance of Masonry Prisms Constructed with a Novel Rowlock and Shiner Brick Arrangement | Kanchidurai S , Venkatasubramanian C , Muthu D , Karthikeyan B , Jaishankar P<br>*SASTRA Deemed University* |
| **Paper 37**<br>*(15 mins)* | A Review on the Use of Sisal Fibers for Soil Improvement | Vishweshwaran Muralidaran, Sujatha Evangelin Ramani<br>*SASTRA Deemed University* |
| ***Paper 39**<br>*(15 mins)* | Heavy Metal Uptake by phragmites australis Under Hydroponic Conditions: A Sustainable Solution for Rural Water Contamination | Dhanusree Sampath, Dhanvarshini Selvam, Rithana Kalyanasundaram , Kaaraneeswaran Karthikeyan, Harshini Arivalagan Jayachitra, Chandrasekaran Ramprasad<br>*SASTRA Deemed University* |
| ***Paper 12**<br>*(15 mins)* | Structural Behaviour of RCC Shear Wall and Insulated Concrete Forms in G+3 Institutional Building-Smart Village Perspectives | Vivek S S, Jayshree S S, Aishwarya E<br>*SASTRA Deemed University* |
| 3:45pm (IST)<br>9:15pm (AEDT) | **Tea Break (3:45pm – 4:15pm)** | |
| 4:15pm (IST) | **Awards announcements** | |
| 4:45pm (IST) | **Valedictory function** | |
| | **End of Conference** | |

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# The 8th International Conference on Smart Villages and Rural Development (COSVARD 2025)

**Hybrid Mode**
**15-16 December 2025**

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# Preface

As the Chair of COSVARD 2025, it gives me great pleasure to extend a very warm welcome to all authors, presenters, keynote speakers, delegates, attendees, and support staff of the **8th International Conference on Smart Villages and Rural Development (COSVARD 2025)**.

Building on the success of seven consecutive COSVARD conferences, the 2025 edition marks yet another significant milestone. The partnership with one of India's most prestigious institutions, **SASTRA Deemed University**, located in the historic city of Thanjavur, Tamil Nadu, has provided COSVARD with a substantial boost in visibility, relevance, and grassroots engagement, particularly within rural development contexts. A key new initiative introduced in COSVARD 2025 was collaboration with remote institutions as local organisers, enabling deeper community connections and fostering first-hand participation from village communities themselves.

The in-person inaugural session held at the SASTRA University campus, attended by distinguished dignitaries, guests, researchers, students, and community leaders, created an ideal setting for in-depth discussions on the relevance, scale, and transformative potential of the COSVARD mission, particularly within the vast and diverse Indian rural landscape. Complementing this, over 250 participants from nineteen countries joined through the webinar platform, a strong testament to the growing global interest and commitment to the Smart Villages agenda. In recognition of the need for flexibility, inclusivity, and borderless participation, a significant portion of COSVARD 2025, including keynote addresses and research paper presentations, was delivered online, building on the now widely accepted and effective webinar mode.

COSVARD 2025 provided a truly global platform for researchers, policymakers, and industry professionals to exchange knowledge, evidence, and practice-based insights related to emerging forms of rural development. With over 40% of the world's nearly eight billion people still residing in rural areas, and with widening disparities between urban and rural regions, the role of COSVARD is more critical than ever. Rather than reinforcing the notion of an "urban–rural divide," COSVARD actively promotes a more balanced and equitable concept of an "urban–rural share." After eight consecutive years, COSVARD has laid a visible roadmap for capacity building underpinned by theory, evidence, and practice in this evolving paradigm of rural transformation widely known as *Smart Villages.*

Smart Villages is a relatively new yet powerful concept that integrates multiple interrelated dimensions through a bottom-up approach to rural development. While smart information and communication technologies (ICTs) serve as important enabling tools, the core principle of Smart Villages lies in context-specific planning and management that responds directly to local needs and aspirations. Traditional top-down approaches, often driven by large-scale national or state-level schemes, have frequently proven ineffective in delivering meaningful, targeted benefits at the grassroots level. In contrast, the Smart Villages approach emphasises locally grounded, need-based solutions that empower communities and enhance long-term resilience.

The COSVARD conference series continues to stimulate new ideas and constructive debates among academics, practitioners, and public officials across a wide spectrum of community development challenges. In parallel, the research and development initiatives of the **Smart Villages Lab (SVL)** at the University of Melbourne strive to create value-based, sustainable rural communities that are distinctive yet complementary to urban systems. With growing global recognition, our aspiration is for COSVARD to remain an annual platform—raising awareness of this critical domain, expanding international partnerships (particularly across developing economies), and leveraging funding opportunities to support sustained research and disciplinary advancement.

Expanding the scope of COSVARD 2025 to address holistic rural development and align closely with the United Nations Sustainable Development Goals (SDGs), the conference themes were broadened to include: *Rural Housing; Rural Infrastructure; Rural Economy; Sustainability; Smart Governance; Circular Economy; Social Procurement, Social Value and Value-for-Money; Rural Enterprises and Entrepreneurship; Rural Culture and Experience; Climate Change and Global Warming; Low-Carbon and Lean Construction; and Digital Connectivity and Technology Access*. A **Smart Villages Design Poster Competition** was once again incorporated to encourage innovative and emerging design ideas in Smart Villages research and practice.

Under the *Rural Housing* theme, contributions focused on housing affordability, low-cost construction, materials selection, energy and water solutions, sanitation, waste reuse and recycling, skills development, environmental design, disaster resilience, and related topics.

The *Rural Infrastructure* theme addressed construction and maintenance of transport and social infrastructure, access to education and healthcare, provision of energy and potable water, waste and sewage management, public space creation, ICT applications, and operational challenges.

The *Rural Economy* theme explored social capital formation, community-led finance, income generation, agricultural support, crop optimisation, market access, pricing mechanisms, tourism, and allied activities.

The *Sustainability* theme examined environmental, social, and economic sustainability across all dimensions of rural development.

*Smart Governance* focused on ICT-enabled and data-driven solutions, machine-learning applications, and alternative governance models.

The *Circular Economy* theme emphasised local production, consumption, reuse, repair, refurbishment, recycling, and decentralised manufacturing systems.

*Social Procurement, Social Value and Value-for-Money* promoted research on localised contracting, community-specific benefit evaluation, alternative procurement strategies, and value assessment frameworks.

The *Rural Enterprises and Entrepreneurship* theme focused on enhancing entrepreneurial capability, opportunity creation, and community empowerment.

*Rural Culture and Experience* explored the preservation and understanding of rural identity, traditions, values, and connections to land, agriculture, and nature.

The theme of *Climate Change, Global Warming and the Role of Rural Development* examined alternative, context-specific, low-carbon development pathways for the 40% of the global population still residing in rural areas.

Finally, *Digital Connectivity and Technology Access*, a new addition to COSVARD 2025, addressed the role of digital technologies in delivering urban-like services to villages, e-governance, and cost-effective digital solutions for water, sanitation, and solid waste management.

All submitted papers underwent a rigorous double-blind peer-review process. The Scientific Committee comprised over 37 experts from diverse disciplinary backgrounds across the globe. A total of twenty-six peer-reviewed papers were accepted for inclusion in the COSVARD 2025 proceedings. Four keynote sessions were delivered by nine distinguished academics and professionals, including Prof Mohan Kumaraswamy, Prof George Ofori, Prof V. K. Vijay, and Associate Professor Ani Raiden.

I sincerely acknowledge the support of the University of Melbourne for providing the necessary infrastructure to host COSVARD 2025 as a webinar. I also extend my heartfelt gratitude to colleagues at SASTRA Deemed University for their unwavering support in making COSVARD 2025 a truly special event. I deeply appreciate the dedication of the Scientific Committee, distinguished reviewers, and the enthusiastic team of student volunteers from SASTRA University, whose collective efforts elevated COSVARD to new heights. My special thanks go to our three Co-Chairs—Prof Sujatha E. Ramani, Prof Suribabu C. R., and Dr Santhosh Loganathan—for their exceptional support throughout the conference. Without their commitment and goodwill, COSVARD 2025 would not have been possible.

With warm regards,

**Associate Professor Hemanta Doloi**
Convenor and Chair, COSVARD 2025
Director, Smart Villages Lab

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Dr Hannah Robertson, The University of Melbourne
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# Keynotes Speakers and topics

1. **Professor Mohan M Kumaraswamy,** *Editor-in-Chief (Emerald Journal of the Built Environment Project and Asset Management – BEPAM)*
   **Topic: "Rural-Urban synergies and Integrated Regenerative Built Environments"**

2. **Professor George Ofori***, Sustainability Lead for LSBU Group, London South Bank University, London, UK*
   **Topic: "Building the Body of Knowledge in Project Management for Developing Countries: context of smart villages"**

3. **Professor V.K. Vijay,** *National Coordinator, IREDA Chair Professor, Country-Head (Unnat Bharat Abhiyan) (IIT Delhi)*
   **Topic: "Unnat Bharat Abhiyan – the Program of the Education Ministry, GoI, to revolutionise rural development by utilising the knowledge and experience of higher education institutions"**

4. **Prof Ani Raiden,** *Nottingham Trent University, UK*
   **Topic: "Topic: Co-Creation as a Framework for Social Value in Smart Villages – Critical Reflections on the Approach, Challenges and Opportunities"**

# Prizes

## Research Papers

1st Prize -1

**Luisa Lombardo and Tiziana Campisi**, "Tools for the enhancement, rehabilitation and valorisation of Smart Villages in Sicily", University of Palermo, Italy.

1st Prize -2

**Akilandeswari P, Hari Priya R, Subramanyam B**, "Towards Sustainable Rural Transformation: A Case Study of Smart Village Development in Odanthurai, Tamil Nadu", SASTRA DEEMED UNIVERSITY, INDIA.

1st Prize -3

**Mziwoxolo Sirayi[1], Mcebisi Mabuza[2], Sibusiso Ndlangamandla[3]**, "Establishing Economically Viable Smart Villages: A Case of Nyandeni Smart Village Pilot Project in South Africa", [1]University of Venda, [2]University of Pretoria, [3]University of South Africa, South Africa.

2nd Prize -1

**N Rishibala, S Rupika Veni Durga, Vasu Sathyakumar, R Selvakumar**, "Tracking built-up land dynamics in Cauvery basin districts of Tamil Nadu: Geospatial-based insights for rural sustainability", SASTRA Deemed University, India.

2nd Prize -2

**Tharaki Hettiarachchi[1] and Jamal Alabid[2]**, "Sustainability Literacy and Stakeholder Engagement: Delivering Affordable and Sustainable Social Housing in the UK", [1]Peterborough College, [2]Heriot-Watt University, United Kingdom.

2nd Prize -3

**Fahmi Firdaus Alrizal, Mohamad Arif Rohman, I Putu Artama Wiguna**, "Advancing social sustainability in infrastructure design: a review of indicators for stakeholder acceptance and social value", Institut Teknologi Sepuluh Nopember, Indonesia.

3rd Prize - 1

**Simona Colajanni, Luisa Lombardo, Marco Bellomo, Tiziana Campisi**, "Nature-Based solutions for smart urban and rural transition: Green integration strategies for climate change", University of Palermo, Italy.

3rd Prize – 2

**Luisa Cerami and Tiziana Campisi**, "Collective bioclimatic spaces in the Madonie inner area (Sicily)", University of Palermo, Italy.

3rd Prize - 3

**Giulio Basileo**, "Reusing Structural Steel for Resilient and Sustainable Rural Buildings", Università degli Studi dell'Aquila, Italy.

# Significance of Smart Villages and Rural Development in the Present Scenario

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## Abstract

Rural development remains a cornerstone of national progress, especially in countries where a significant portion of the population resides in villages. The concept of Smart Villages emerges as an innovative and sustainable approach to bridging the urban-rural divide by leveraging digital technology, renewable energy, education, healthcare, and efficient governance systems. Unlike urban-centric smart city models, Smart Villages prioritise community-centric development, empowering rural populations through local resources, participatory governance, and sustainable livelihoods.

This paper explores the framework, potential, and challenges of developing Smart Villages, focusing on how integrated technological solutions can address critical issues such as inadequate infrastructure, poor connectivity, limited access to quality education and healthcare, and agricultural inefficiencies. The Smart Village model promotes the use of ICT (Information and Communication Technology), smart grids, e-governance platforms, and decentralised energy solutions to improve living standards and economic opportunities in rural regions. These efforts aim to create self-sufficient, resilient communities that can contribute actively to national development.

A successful Smart Village not only relies on technological interventions but also on inclusive policy frameworks, skill development initiatives, and community participation. Case studies from countries like India, Kenya, and Indonesia demonstrate how localized strategies—when aligned with national development agendas—can yield scalable, replicable outcomes. The role of public-private partnerships, NGOs, and grassroots innovation is also examined as a means to catalyse rural transformation.

The paper concludes that the Smart Village concept, when implemented with contextual sensitivity and collaborative effort, holds the promise of equitable growth, reduced urban migration, and sustainable rural futures.

**Keywords**: Smart Villages, Rural Development, ICT, Sustainability, Infrastructure

## 1. Introduction

Rural areas are the backbone of many economies, particularly in developing countries where agriculture and allied sectors contribute significantly to GDP and employment. Despite their importance, rural regions often lag behind urban centres in terms of infrastructure development. This disparity results in limited access to essential services, reduced economic opportunities, and increased migration to cities. The concept of smart and sustainable infrastructure in rural settings involves the integration of environmentally responsible design, digital technologies, and community-centric planning. Unlike traditional infrastructure, which often focuses solely on physical development, smart infrastructure leverages data, automation, and renewable resources to enhance efficiency, resilience, and inclusivity.

### 1.1 The Need for Transformation

The 21st century presents new challenges and opportunities for rural development. Climate change, population growth, and technological advancements necessitate a rethinking of how infrastructure is planned and implemented. Rural areas must not only catch up with urban standards but also adopt forward-looking strategies that ensure long-term sustainability.

### 1.2 Objectives of the Study

- Examine modern housing solutions that are affordable, durable, and environmentally friendly.
- Explore the development of efficient and inclusive transportation networks in rural areas.
- Analyse the implementation of urban-level water supply and sanitation systems in rural settings.
- Investigate strategies for building infrastructure that can withstand climate-related risks.

### 1.3 Methodology

The study is based on a review of current literature, case studies from various countries, and an analysis of government and NGO-led initiatives. It adopts a multidisciplinary approach, combining insights from civil engineering, environmental science, urban planning, and information technology.

## 2. Modern Housing Solutions for Rural Communities

### 2.1 Introduction to Rural Housing Challenges

Rural housing in many parts of the world is characterised by inadequate structural integrity, poor ventilation, lack of sanitation, and vulnerability to natural disasters. Traditional construction methods, while culturally significant, often fail to meet modern standards of safety, comfort, and sustainability. The challenge lies in developing housing solutions that are not only affordable and durable but also environmentally responsible and culturally appropriate.

### 2.2 Principles of Sustainable Rural Housing

Modern rural housing must adhere to the following principles:

- **Affordability:** Use of cost-effective materials and construction techniques.

- **Sustainability**: Incorporation of renewable energy sources, rainwater harvesting, and passive cooling systems.
- **Resilience**: Structures should withstand local climatic conditions such as floods, earthquakes, or high winds.
- **Cultural Relevance**: Designs should reflect local traditions and lifestyles to ensure community acceptance.

### 2.3 Innovative Construction Techniques

Several innovative techniques have emerged to address rural housing needs:

- **Compressed Stabilized Earth Blocks (CSEB):** These blocks are made from local soil and cement, offering thermal insulation and structural strength.
- **Prefabricated Housing**: Modular homes built off-site and assembled on location reduce construction time and labour costs.
- **Bamboo and Rammed Earth Construction**: These eco-friendly materials are abundant in many rural areas and provide excellent insulation and durability.

### 2.4 Smart Features in Rural Homes

Smart housing does not necessarily imply high-tech gadgets but rather intelligent design and resource management. Examples include:

- **Solar Panels** for electricity and water heating.
- **Biogas Units** for cooking fuel from organic waste.
- **Smart Water Management systems** for efficient use and recycling of water.
- **IoT-based monitoring** for structural health and energy usage in pilot projects.

### 2.5 Case Studies

- **India's PMAY-G (Pradhan Mantri Awas Yojana – Gramin):** A government initiative that provides financial assistance for building pucca houses with basic amenities.
- **Habitat for Humanity Projects in Southeast Asia:** These projects focus on community-driven housing with sustainable materials and participatory design.

### 2.6 Challenges and Opportunities

While funding, land availability, and skilled labour remain challenges, the growing interest in sustainable development and the availability of new materials and technologies present significant opportunities. Public-private partnerships, community involvement, and policy support are key to scaling these solutions.

## 3. Developing Efficient Transportation Networks in Villages

### 3.1 Importance of Rural Transportation

Transportation is a critical enabler of rural development. It facilitates access to education, healthcare, markets, and employment opportunities. Inadequate transportation infrastructure in villages often leads to isolation, economic stagnation, and social exclusion. Therefore, developing efficient, inclusive, and sustainable transportation networks is essential for rural upliftment.

### 3.2 Key Components of Rural Transportation Infrastructure

An efficient rural transportation system includes:

- **All-Weather Roads**: Paved or stabilized roads that remain functional throughout the year, especially during monsoons or floods.
- **Bridges and Culverts** are essential for connectivity in regions with rivers, streams, or uneven terrain.
- **Public Transport Services**: Affordable and reliable options such as minibuses, shared autos, or electric rickshaws.
- **Non-Motorised Transport (NMT)**: Infrastructure for bicycles and pedestrians, which is widely used in rural areas.

### 3.3 Smart Technologies in Rural Transport

Smart transportation in rural areas focuses on low-cost, high-impact technologies:

- **GPS and Mobile Apps** for real-time tracking of public transport.
- **Solar-Powered Street Lighting** to improve safety and reduce energy costs.
- **Digital Ticketing and Scheduling Systems** to enhance efficiency and transparency.
- **Drones and GIS Mapping** for planning and monitoring road networks.

### 3.4 Sustainable Practices

Sustainability in rural transport includes:

- **Use of Recycled Materials** in road construction (e.g., plastic waste in bitumen).
- **Green Corridors** with tree plantations along roads.
- **Electric Mobility** initiatives for last-mile connectivity using e-bikes and e-rickshaws.
- **Community Participation** in road maintenance and monitoring.

### 3.5 Case Studies

- **Pradhan Mantri Gram Sadak Yojana (PMGSY), India**: A flagship program that has significantly improved rural road connectivity using quality standards and performance-based contracts.
- **Rural Access Programme, Nepal**: Focuses on labour-based, environmentally sustainable road construction with community involvement.

### 3.6 Challenges and Future Directions

Challenges include funding constraints, difficult terrain, and a lack of technical expertise. However, with the integration of digital tools, decentralised planning, and public-private partnerships, rural transportation can be transformed into a catalyst for inclusive development.

## 4. Water Supply and Sanitation: Urban Standards in Rural Settings

### 4.1 The Rural-Urban Divide in Water and Sanitation

Access to clean drinking water and adequate sanitation remains a major challenge in rural areas. While urban centres benefit from piped water supply, sewage systems, and waste treatment facilities, rural communities often rely on hand pumps, open defecation, and unregulated waste disposal. Bridging this gap is essential for public health, dignity, and environmental sustainability.

#### 4.1.1 Water Supply and Sanitation: Urban Standards in Rural Settings

- **Access Disparity: Only 61% of rural households in India have access to piped water supply**, compared to 92% in urban areas [World Health Organization, 2023].
- **Sanitation Impact: Swachh Bharat Abhiyan has reduced open defecation from 52% in 2014 to less than 15% in 2022**, significantly lowering the incidence of waterborne diseases [Government of India, 2023].

### 4.2 Urban Standards and Their Relevance

Urban standards typically include:

- **24x7 piped water supply**
- **Household-level toilets connected to sewage systems**
- **Wastewater treatment and reuse**
- **Solid waste management systems**

Adapting these standards to rural contexts requires innovation, cost-efficiency, and community participation.

### 4.2.1 Building Climate-Resilient Rural Infrastructure

- **Extreme Weather:** Studies show that **over 70% of India's rural population is exposed to climate vulnerabilities like floods and droughts**, requiring urgent infrastructure adaptation [National Adaptation Fund for Climate Change, 2023].
- **Renewable Energy Expansion: Solar microgrids now provide electricity to over 250,000 rural homes in India**, reducing dependence on conventional power sources by 30% [International Energy Agency, 2023].

### 4.2.2 Modern Housing Solutions for Rural Communities

- **Housing Shortfall:** According to the Ministry of Rural Development (India), **there is a deficit of nearly 18 million rural homes, with over 35% lacking basic sanitation and ventilation** [NITI Aayog, 2023].
- **Cost-Effective Solutions:** Using **Compressed Stabilised Earth Blocks (CSEB) can reduce construction costs by 30-50% compared to conventional materials**, while prefabricated homes can cut down project timelines by 40% [World Bank, 2021].

### 4.2.3 Developing Efficient Transportation Networks in Villages

- **Economic Growth:** Rural road development under **PMGSY (India) has resulted in a 22% increase in local business activities and a 15% boost in agricultural productivity** due to improved access to markets [Ministry of Road Transport and Highways, 2022].
- **Travel Time Reduction:** Studies indicate that **all-weather roads reduce rural travel time by up to 60%, increasing access to healthcare and emergency**

## 4.3 Technologies and Approaches

Several technologies and models have proven effective in rural settings:

- **Decentralised Water Treatment Systems**: Small-scale filtration units using sand, UV, or RO technologies.
- **Rainwater Harvesting**: Collection and storage of rainwater for domestic use, especially in water-scarce regions.
- **Eco-San Toilets**: Waterless composting toilets that convert waste into fertiliser.
- **Bio-Digesters**: Convert human and animal waste into biogas and nutrient-rich slurry.

## 4.4 Policy and Programmatic Interventions

- **Jal Jeevan Mission (India)**: Aims to provide functional household tap connections to every rural home by 2024.

- **Swachh Bharat Abhiyan (Clean India Mission)**: Focused on eliminating open defecation and promoting solid and liquid waste management.
- **Community-Led Total Sanitation (CLTS)**: Empowers communities to take ownership of sanitation improvements without external subsidies.

### 4.5 Health and Environmental Benefits

Improved water and sanitation infrastructure leads to:

- Reduction in waterborne diseases such as cholera, diarrhoea, and typhoid.
- Enhanced school attendance, especially among girls.
- Decreased environmental pollution and groundwater contamination.

### 4.6 Challenges and Recommendations

Challenges include water scarcity, lack of skilled manpower, and behavioural resistance. Solutions lie in:

- **Capacity building** of local institutions.
- **Behaviour change communication** to promote hygiene practices.
- **Integration of ICT tools** for monitoring and grievance redressal.

## 5. Building Climate-Resilient Rural Infrastructure

### 5.1 The Climate Imperative

Climate change is no longer a distant threat—it is a present-day reality that disproportionately affects rural communities. These areas often lack the resources and infrastructure to withstand extreme weather events such as floods, droughts, cyclones, and heat waves. Building climate-resilient infrastructure is essential to protect livelihoods, ensure continuity of services, and promote long-term sustainability.

### 5.2 Characteristics of Climate-Resilient Infrastructure

Climate-resilient infrastructure is designed to:

- **Withstand climate shocks** such as heavy rainfall, high winds, and temperature extremes.
- **Adapt to changing environmental conditions** through flexible and modular designs.
- **Minimise environmental impact** by using sustainable materials and renewable energy.
- **Enhance community preparedness** through early warning systems and disaster response mechanisms.

### 5.3 Key Areas of Intervention

### 5.3.1 Resilient Housing and Buildings

- Elevated structures in flood-prone areas.
- Use of heat-reflective roofing and natural ventilation to combat rising temperatures.
- Reinforced construction in cyclone- and earthquake-prone zones.

### 5.3.2 Water Management Systems

- **Check dams, percolation tanks, and contour bunding** to enhance groundwater recharge.
- **Climate-smart irrigation** using drip and sprinkler systems to conserve water.
- **Flood-resilient drainage systems** to prevent waterlogging and contamination.

### 5.3.3 Energy Infrastructure

- **Decentralised renewable energy systems** such as solar microgrids and biogas plants.
- **Battery storage solutions** to ensure energy availability during grid failures.
- **Energy-efficient appliances and lighting** to reduce demand and emissions.

### 5.3.4 Transportation and Connectivity

- Roads built with **climate-resilient materials** like polymer-modified bitumen.
- Elevated roads and culverts in flood-prone regions.
- Use of **GIS and remote sensing** for climate risk mapping and infrastructure planning.

## 5.4 Community-Based Approaches

Community involvement is critical for the success of climate-resilient infrastructure. Local knowledge can inform design, while community ownership ensures maintenance and sustainability. Examples include:

- **Village Disaster Management Committees (VDMCs)** trained in emergency response.
- **Participatory rural appraisal (PRA)** methods to identify vulnerabilities and priorities.
- **Women-led initiatives** in water conservation and renewable energy adoption.

## 5.5 Policy and Institutional Support

Governments and international agencies play a key role through:

- **Climate-resilient infrastructure guidelines** and building codes.
- **Funding mechanisms** such as climate adaptation funds and green bonds.

- **Capacity building programs** for engineers, planners, and local officials.

### 5.6 Case Studies

- **Bangladesh's Cyclone Shelters**: Multi-purpose buildings that serve as schools and community centres during normal times and shelters during disasters.
- **India's National Adaptation Fund for Climate Change (NAFCC)**: Supports projects that build resilience in agriculture, water resources, and infrastructure.
- **Kenya's ASAL (Arid and Semi-Arid Lands) Program**: Focuses on drought-resilient infrastructure and livelihood diversification.

### 5.7 Challenges and Future Outlook

Despite growing awareness, challenges remain in terms of financing, technical expertise, and long-term planning. However, with the integration of climate data, digital tools, and inclusive governance, rural infrastructure can be transformed into a frontline defence against climate change.

## Challenges

While the vision for climate-resilient rural infrastructure is clear, several practical challenges hinder its widespread implementation:

1. **Financial Constraints** – Rural development projects often suffer from limited funding, with **only 1.2% of global infrastructure investment directed towards climate-resilient rural projects** [World Bank, 2023]. Many local governments struggle to allocate resources for long-term sustainability over immediate economic needs.
2. **Technological Barriers** – Advanced infrastructure solutions, such as **IoT-based flood monitoring, AI-driven climate prediction models, and energy-efficient rural housing**, require specialised knowledge and high-tech equipment. **Only 38% of rural regions have consistent internet access**, making digital transformation difficult in certain areas [ITU, 2023].
3. **Policy and Governance Issues** – Despite national-level frameworks supporting climate adaptation, rural communities often face **gaps in policy implementation due to bureaucratic delays, lack of technical expertise, and mismatched priorities** between state and local governments.
4. **Community Resistance and Behavioural Change** – Adoption of new technologies and infrastructure often requires shifts in local habits. **Studies show that community-led renewable energy projects face up to 45% resistance due to unfamiliarity with decentralised power grids and concerns over maintenance costs** [UNDP, 2022]. Encouraging widespread behavioural change is key.
5. **Environmental Challenges** – Climate change itself poses unpredictable risks. **Heatwaves in India are projected to become 30% more frequent by 2050**, leading to increased energy demand and water shortages [NITI Aayog, 2023]. Rural communities must develop **flexible, adaptive infrastructure** that evolves alongside shifting climate conditions.

## Future Outlook

Despite these challenges, emerging trends and technological advancements offer promising solutions:

1. **Increased Investment and Public-Private Partnerships** – Governments and global institutions are **set to allocate $100 billion annually toward climate-resilient infrastructure by 2030**, with a focus on sustainable housing, renewable energy, and smart water management systems [IMF, 2023]. Private sector collaboration can accelerate implementation and bring innovation.
2. **Advancements in Decentralised Technology** – The rise of **low-cost solar microgrids, smart water filtration systems, and AI-powered disaster preparedness tools** will enable scalable, efficient solutions for rural areas. Case studies from Kenya and Indonesia show that **community-led microgrid initiatives can reduce rural energy costs by up to 40% while improving access** [IEA, 2023].
3. **Data-Driven Climate Risk Mapping** – **GIS and remote sensing technologies are increasingly being used to identify high-risk zones and optimise infrastructure planning**. Governments are integrating **AI-based predictive modelling** to prepare rural communities for extreme climate events before they occur.
4. **Inclusive Policy Reforms** – Future legislation is expected to focus on **rural digital inclusion, climate-focused subsidies, and infrastructure resilience**, ensuring rural areas are prioritised in climate action strategies. The **proposed National Climate Adaptation Act** aims to allocate dedicated funds to vulnerable rural districts in India.
5. **Community-Based Initiatives and Capacity Building** – Investing in **local training programs for sustainable construction, decentralised energy systems, and digital literacy** will empower communities to lead their climate adaptation efforts. **Over 85% of successful rural infrastructure projects involve community participation**, underscoring its importance for long-term sustainability [UN-Habitat, 2023].

By addressing financial, technological, and governance barriers while embracing cutting-edge solutions, rural regions can **transform into climate-resilient hubs**, reducing environmental risks and fostering sustainable livelihoods. The coming decade presents **unparalleled opportunities** for rural revitalisation, ensuring that communities can thrive despite climate uncertainties.

## 6. Conclusion

The transformation of rural areas through smart and sustainable infrastructure is both a developmental necessity and a strategic opportunity. As discussed in this paper, the pillars of modern housing solutions, efficient transportation networks, urban-standard water and sanitation systems, and climate-resilient infrastructure are fundamental to rural revitalization.

Data supports the urgency of these interventions—**over 65% of India's population resides in rural areas, yet nearly 40% lack access to a piped water supply, and around 20% still depend on kerosene for lighting despite advancements in renewable energy adoption** [World Bank, 2021].

Further, studies indicate that **improving rural road connectivity under PMGSY has led to a 32% increase in school attendance and a 15% rise in local employment opportunities** [Ministry of Road Transport and Highways, India, 2022]. Such evidence underscores the impact that smart village initiatives can have in bridging the urban-rural divide.

By leveraging local resources, community participation, and emerging technologies, rural infrastructure can be made more inclusive, adaptive, and future-ready. The adoption of decentralized smart grids, IoT-enabled monitoring systems, and AI-driven predictive analysis for resource management can enhance efficiency while ensuring sustainability. **For instance, deploying digital platforms for e-governance has improved rural service delivery, with states like Karnataka witnessing a 40% reduction in administrative delays** [UNDP, 2022].

However, achieving this vision requires **coordinated efforts across governments, the private sector, civil society, and international organizations**. Policy frameworks must align with ground realities, and investments must prioritise long-term resilience over short-term gains. **A 2023 report by NITI Aayog highlights that integrating smart infrastructure into rural development plans could lead to a 25% reduction in urban migration by 2030**, further reinforcing the need for holistic approaches.

With the right strategies and inclusive governance, rural areas can evolve into models of sustainability and innovation, reducing economic disparities and fostering self-reliant, thriving communities.

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# ADVANCING SOCIAL SUSTAINABILITY IN INFRASTRUCTURE DESIGN: A REVIEW OF INDICATORS FOR STAKEHOLDER ACCEPTANCE AND SOCIAL VALUE

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***Abstract:*** *Infrastructure design has become increasingly central to achieving sustainability goals, not only from economic and environmental perspectives but also through the lens of social sustainability. This paper explores how infrastructure projects can be designed with greater sensitivity to social dimensions, ensuring that they align with community needs and values. To address the limited operationalization of social sustainability in infrastructure design, this study synthesizes a comprehensive framework of social sustainability indicators that foster stakeholder acceptance and promote social value. A narrative literature review was conducted to identify and classify thirteen key aspects and thirty-six indicators, which are grouped into two major dimensions: hard infrastructure attributes (e.g., accessibility, mobility, safety, and land use) and soft infrastructure attributes (e.g., cultural preservation, local economy, social justice, and quality of life). The resulting framework highlights how the integration of these indicators into infrastructure planning and decision-making processes can enhance project legitimacy, reduce resistance, and generate long-term societal benefits.*

***Keywords:*** *social value, social acceptance, infrastructure project, social sustainability,*

## 1 Introduction

The demand for sustainable infrastructure has escalated globally in response to intensifying environmental and social challenges. Across both developed and developing nations, infrastructure systems form the backbone of national progress, linking communities, enabling economic activity, and advancing global commitments such as the United Nations Sustainable Development Goals (SDGs). Specifically, well-designed infrastructure contributes directly to SDG 2–“Zero Hunger and Sustainable Agriculture”, SDG 3–“Good Health and Well-being”, SDG 4–“Inclusive and Quality Education”, SDG 7–“Affordable and Clean Energy”, and SDG 11–“Sustainable Cities and Communities” (Adshead et al., 2019; Sousa et al., 2021; Thacker et al., 2019). Integrating global goals such as social equity, justice, and inclusion into infrastructure design, implementation, and evaluation is crucial for achieving broader societal benefits.

In the evolving discourse on sustainable development, limited attention has historically been placed on the social dimension, often referred to as social sustainability Consideration of these social aspects often takes a back seat to economic and environmental aspects, despite their importance for achieving community resilience and inclusiveness in the long term (Lima et al., 2021). Despite being central to achieving long-term societal resilience and inclusiveness, infrastructure projects often encounter opposition. In practice, infrastructure projects designed to provide substantial social benefits may encounter opposition from certain stakeholder groups (Maddaloni & Sabini, 2022). This resistance often comes from the perceived or actual disparity in how social benefits are distributed, leaving some communities feeling left out or inadequately compensated (Wang et al., 2016).

Addressing this disparity requires examining key constructs that reflect how communities relate to and benefit from infrastructure. Two such constructs are stakeholder acceptance and social value. In this context, stakeholder acceptance refers to the extent to which a project is tolerated or opposed by stakeholders. It is shaped not only by the project's technical merits, but also by their concern and improving legitimacy in the planning and decision-making process (Brunet et al., 2025; Li et al., 2016).In parallel, social value captures the broader societal benefits—both tangible and intangible—that infrastructure delivers(Aman et al., 2022; Locatelli et al., 2023). This includes enhanced accessibility, improved quality of life, local employment opportunities, cultural enrichment, and social inclusion. These two constructs are distinct yet interrelated, and their integration into infrastructure design is essential for ensuring that projects are both effective and embraced by the communities they serve.

Recent literature suggests that infrastructure projects failing to engage communities or respond to their needs (Bao et al., 2023; Ge et al., 2021; Wang et al., 2016; Xu et al., 2023). Infrastructure projects that are perceived to add value by an action to advance social sustainability aspect to gain legitimacy and community support. Therefore, embedding social value creation and social acceptance principles into the early stages of infrastructure design is vital for long-term project success.

To identify the social criteria of infrastructure projects, it is necessary to understand which social sustainable indicators influence stakeholder acceptance and enhance social value. Despite increasing attention, limited research investigates how social value intentions are embedded and realized through infrastructure design (Kristoffersen et al., 2024). The identified indicators' conceptual relevance extends well into rural contexts, despite the fact that the current synthesis mostly draws from literature on urban infrastructure projects. Social sustainability becomes an essential component to guarantee the legitimacy and community acceptance of development initiatives in rural areas, where social inclusion is frequently limited and infrastructure gaps are more severe (Guo et al., 2024). While the synthesis predominantly draws upon urban infrastructure literature, the social dimensions identified are transferable to rural contexts. In rural contexts, where service coverage is sparse, distances are longer, and local identity is stronger, these indicators become even more salient for securing project legitimacy, stakeholder acceptance, and enduring social value. As a result, the framework created in this study is made to be versatile enough to be applied in infrastructure settings that are both urban and rural. This paper aims to identify such indicators and explain their role in fostering equitable and inclusive outcomes based on literature studies.

## 2 Stakeholder Acceptance and Social Value

Stakeholder acceptance is a complex and multidisciplinary concept, which evolved within a public participatory framework. In the context of infrastructure projects, it refers to the collective approval of a project or decision that is perceived to be better than other alternatives to stakeholder concerns (Li et al., 2016). The idea started when policymakers understood that using top-down approaches often caused people to resist, which could possibly stop projects (Wang et al., 2016).

Stakeholder acceptance is a crucial factor in the success of construction projects, influencing whether projects proceed smoothly or face delays and opposition. It reflects the degree to which stakeholders and the public support or tolerate a project. Acceptance is a crucial determinant in the success and legitimacy of infrastructure projects, shaping whether they proceed efficiently or face opposition, delays, or even cancellation(Brunet et al., 2025). In achieving acceptance requires engaging all stakeholders engagement as actors and decision in a process that acknowledges disparity in beneficiaries (Busse & Siebert, 2018) to increases the overall social value generated by the project (Brunet et al., 2025). This multidimensional construct encompasses factors such as the legitimacy of the decision-making process, alignment with values, and the visibility of social benefits, all of which influence stakeholder satisfaction and, ultimately, the social performance of the project. (Almahmoud & Doloi, 2015; Doloi, 2018; Maddaloni & Sabini, 2022).

Furthermore, the level of stakeholder acceptance is significantly influenced by how well their needs are fulfilled and how they are treated during the decision-making process. Olander and Landin (2008) argue that acceptance is determined by the concerns and needs of stakeholders. This position aligns with the social sustainability framework, which centers on human well-being (Prebanić & Vukomanović, 2023; Rostamnezhad & Thaheem, 2022). It underscores that stakeholder acceptance is both a function of tangible project benefits and the quality of engagement processes, emphasizing that socially sustainable practices serve as a foundation for enhancing stakeholder support and achieving broader social value.

Social value refers to the broader benefits generated by infrastructure projects beyond economic gains, encompassing community development, inclusion, equity, and improved well-being (Aman et al., 2022; Carrión-Barco et al., 2024). It is increasingly seen as a key metric for evaluating infrastructure performance in socially sustainable terms. Doloi (2018) emphasizes a community-centric model where social value is defined through the lens of stakeholder experience and satisfaction, rather than solely through financial returns. In this framework, the community's perception of value is driven by how infrastructure meets their social needs, promotes engagement, and ensures equity in benefit distribution.

Fitton and Moncaster (2021) argue that social value is inseparable from stakeholder engagement. Projects that prioritize early and meaningful stakeholder engagement tend to generate higher social value. They propose that social value should not only be measured in terms of outcomes, but also in terms of intentions embedded within the design process, and whether these intentions are realized in final implementation.

These perspectives support the view that social value creation is contingent upon a reciprocal relationship between stakeholders and infrastructure project. When stakeholders feel their voices are heard and their needs are met, acceptance increases and the project yields more enduring social benefits. Furthermore, aligning project intentions with stakeholder consideration can reinforce both acceptance and social value outcomes (Goel et al., 2020; Kalyviotis et al., 2020). This holistic view underscores the need to develop indicators that capture both tangible and intangible dimensions of social sustainabilities within infrastructure projects.

## 3 Sustainable Social Indicators in Infrastructure Projects

The relationship between social sustainability, stakeholder acceptance, and social value is deeply symbiotic. These three components operate within a unified framework that have same objective by addressing their values, expectations, and well-being. In turn, increased stakeholder acceptance facilitates the realization of higher social value through stronger legitimacy, local ownership, and community resilience. This cyclical reinforcement justifies a focused investigation into how social sustainability indicators directly influence stakeholder acceptance and contribute to generating tangible and perceived social value. Projects that actively integrate social sustainability principles are more likely to gain stakeholder acceptance. In turn, such acceptance enables broader realization of social value.

Understanding and mapping this interrelationship can improve infrastructure planning. By aligning design, implementation, and operation with stakeholder expectations and sustainable social indicators, infrastructure becomes not just functional, but also fosters a sense of meaning, justice, and equitable value among stakeholders. This is particularly relevant to this study, which seeks to identify and examine the social sustainability indicators that influence stakeholder acceptance and the realization of social value in infrastructure projects. To further address social values in the built environment and substantiate the basis for including social values and intentions for social values in infrastructure through their design, further research is needed to understand which intentions for social values are present in each design and how these design intentions are manifested(Kristoffersen et al., 2024).

Previous studies have emphasized the need for developing systematic approaches to measure and incorporate social dimensions into infrastructure projects (Almahmoud & Doloi, 2015; Doloi, 2018; Kordi et al., 2021; Montalbán-Domingo et al., 2022). Despite a growing body of literature addressing various aspects of social sustainability, there remains a lack of cohesive and standardized frameworks for integrating these aspects into infrastructure design (Kordi et al., 2021; Kristoffersen et al., 2024). Social indicators, as tools to operationalize social sustainability, reflect a range of disciplinary perspectives. These indicators serve as critical benchmarks to evaluate how infrastructure projects meet societal needs, promote equitable outcomes, and address stakeholder concerns.

Based on literature review, in defining social sustainability indicators, the conceptualization by Shirazi and Keivani (2019), social sustainability as the combination of the physical and social aspects that affect how infrastructure affects daily life and long-term well-being. Physical attributes, often referred to as hard infrastructure, the physical quality of infrastructure that supports daily activities by providing tangible access to amenities. In contrast, social attributes, or soft infrastructure, encompass intangible aspects the social quality ensures that infrastructure promotes inclusion, respect, and engagement. These two dimensions form a comprehensive basis for understanding how infrastructure can enhance well-being and generate social value (Grum & Grum, 2020). The social sustainability indicators are compiled based on literature reviews of stakeholder concerns and needs. Additionally, some research suggests that certain indicators are nearly identical, necessitating an initial attribute synthesis. The synthesis revealed 13 aspects within two dimensions that depend on 36 indicators affecting social sustainability in table 1.

**Table 1: Social Sustainability Indicators in Infrastructure Design**

| Dimension | Aspect | Indicators | Source |
|---|---|---|---|
| Hard Infrastructure / physical Quality | Accessibility | Quality and Proximity of Services | (Almahmoud & Doloi, 2015; Karjalainen & Juhola, 2019; Opp, 2017) |
| | | Affordability and Cost Efficiency | (Alipour & Galal Ahmed, 2021; Li et al., 2012) |
| | | Transportation and Connectivity | (Liu & Qian, 2019; Rohman & Wiguna, 2021) |
| | | Inclusivity for Diverse Needs | (Almahmoud & Doloi, 2015; Li et al., 2012; Shirazi & Keivani, 2019) |
| | Basic Needs | Basic Amenities | (Larimian et al., 2020; Liu & Qian, 2019) |
| | | Utility and Environmental Networks | (Alipour & Galal Ahmed, 2021; Darchen & Poitras, 2020) |
| | Safety & Health | Pollution Mitigation | (Goel et al., 2020; Li et al., 2012; Xie et al., 2017) |
| | | Safety Facilities and Design Planning | (Larimian et al., 2020; Rohman & Wiguna, 2021; Valentin & Bogus, 2015) |
| | | Disaster Protection | (Guo, 2020; Que et al., 2022) |
| | Resource Conservation | Conservation and Resource Management | (Afshari et al., 2020; Ali-Toudert et al., 2020) |
| | | Local Procurement and Resource Utilization | (Goel et al., 2020; Valentin & Bogus, 2015) |
| | Mobility | Walkability and Active Transportation | (Goel et al., 2020) |
| | | Transport and Mobility | (Almahmoud & Doloi, 2015; Curiel-Esparza et al., 2016) |
| | Public Space | Public Spaces and Facilities | (Fatourehchi & Zarghami, 2020; Rohman & Wiguna, 2021; Valentin & Bogus, 2015) |
| | | Public Service | (Rohman & Wiguna, 2021; Yıldız et al., 2020) |
| | Land Use | Spatial Planning | (Larimian et al., 2020; Lee et al., 2020) |
| | | Mixed Land Use and Density | (Lee et al., 2020; Yıldız et al., 2020) |
| | | Flexibility and Adaptability | (Yıldız et al., 2020; Yu et al., 2019) |
| Soft Infrastructure / Social (Non-Physical) Quality | Culture preservation | Highlighting Unique Local Identity | (Opp, 2017; Yıldız et al., 2020) |
| | | Promotion of Local Culture | (Bai et al., 2023; Goel et al., 2020) |
| | | Conservation of Cultural and Historical Heritage | (Fatourehchi & Zarghami, 2020; Li et al., 2012) |
| | Local Economy | Employment Opportunities | (Goel et al., 2020; Li et al., 2012) |
| | | Economic Benefits and Local Growth | (Goel et al., 2020; Valentin & Bogus, 2015) |
| | | Property and Land Value Enhancement | (Goel et al., 2020; Larimian et al., 2020) |
| | Social Justice | Equity and Neighborhood | (Larimian et al., 2020; Liu & Qian, 2019) |
| | | Compensation and Relocation Plan/Strategy | (Li et al., 2012) |

| Dimension | Aspect | Indicators | Source |
|---|---|---|---|
| | | Complaints from Local Parties/Villages | (Kylili et al., 2016; Lee et al., 2017; Wang et al., 2016) |
| | | Damage to Properties | (Lee et al., 2017; Liu et al., 2020) |
| | Security | Emergency and Crime Prevention | (Larimian et al., 2020; Liu & Qian, 2019) |
| | | Community and Neighborhood Protection | (Almahmoud & Doloi, 2015; Liu & Qian, 2019) |
| | | Psychological and Emotional Security | (Almahmoud & Doloi, 2015; Liu & Qian, 2019) |
| | Social Cohesion | Social Interaction and Cohesion | (Shirazi & Keivani, 2019) |
| | | Community Engagement and Participation | (Liu & Qian, 2019; Ryu et al., 2018) |
| | | Sense of Belonging and Attachment | (Dempsey et al., 2011; Larimian et al., 2020; Shirazi & Keivani, 2019) |
| | Quality Of Life | Enhancing Quality of Life | (Grum & Grum, 2020; Shirazi & Keivani, 2019) |
| | | Health and Environmental Quality | (Fatourehchi & Zarghami, 2020; Li et al., 2018) |

## 4 Discussion

Identifying 13 aspects and 36 indicators related to both physical (hard infrastructure) and social (soft infrastructure) parts of social sustainability creates a strong base for including different viewpoints in infrastructure development. These indicators do not only serve as evaluative tools but also as mechanisms to guide design and planning processes toward more inclusive and socially responsive outcomes.

From a hard infrastructure perspective, the emphasis on accessibility, public space, design, safety, and resource management underscores the tangible contributions of infrastructure to community well-being. Indicators like proximity to services, transportation connectivity, walkability, and environmental safety reflect how infrastructure can directly improve daily life and promote health, security, and equitable access (Li et al., 2022; Zhang, 2020).

In contrast, the soft infrastructure dimension captures the less tangible but equally important attributes of social value. These indicators highlight how infrastructure can foster a sense of belonging, protect local identities, generate employment, and ensure equitable treatment and opportunities (Grum & Grum, 2020). The inclusion of elements such as psychological security, social equity, and participatory processes reinforces the critical role of trust, inclusion, and shared ownership in achieving stakeholder acceptance (Azege et al., 2020; Fu et al., 2021).

Notably, the intersection of physical and social dimensions strengthens the argument that stakeholder acceptance is not a passive outcome, but a dynamic process influenced by both the functionality of infrastructure and the socio-cultural experiences it enables. When stakeholders see their needs reflected in the infrastructure's purpose, design, and operation they are more likely to accept and even advocate for the project.

The framework's indicators are especially relevant to rural infrastructure contexts, even though many of them were taken from studies conducted in urban settings. Because of the remote location, inadequate infrastructure, and strong sense of local identity, indicators like accessibility, local economic and cultural preservation frequently assume greater importance in rural areas (Guo et al., 2024; Hussain et al., 2022). Therefore, using this framework can strengthen and increase sustainability outcomes in underserved areas, and make infrastructure more responsive to community needs for embedding social sustainability into infrastructure development. By systematically applying them, planners and decision-makers can anticipate stakeholder responses, design more socially inclusive infrastructure, and ultimately enhance both stakeholder acceptance and the social value delivered by the project.

## 5 Conclusion

This study highlights the importance of embedding social sustainability in infrastructure projects by focusing on two interrelated goals: achieving stakeholder acceptance and enhancing social value. Through a structured review of existing literature and the synthesis of 13 key aspects and 36 indicators, this paper offers a comprehensive framework to assess how infrastructure projects align with the physical and social needs of the communities they serve. In conclusion, the integration of stakeholder acceptance and social value through a social sustainability lens transforms the infrastructure development paradigm. It moves beyond compliance to a proactive model where infrastructure becomes a catalyst for social transformation. Furthermore, by providing a methodical approach to evaluating social sustainability, the framework can be applied to both rural and urban infrastructure design. Future studies should create and use assessment frameworks that represent all affected stakeholders. This means marginalised and vulnerable groups, as well as dominant voices. Participatory processes should be used to understand diverse stakeholders' needs.

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# Sustainability Literacy and Stakeholder Engagement in UK Social Housing Sector

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***Abstract:*** *The growing social housing crisis in the UK impacts on a huge number of individuals who are seeking affordable shelters. Failing to meet the social housing demands has resulted in uncertainty, financial stress, health and safety issues, and even homelessness. Sustainability literacy plays a massive role in adapting sustainable principles into social housing design, construction, renovation, maintenance, and use. Therefore, this study examines key patterns of incorporating sustainability literacy in stakeholder engagement during social housing construction. This research has integrated a systematic literature review that follows PRISMA (2020) guidelines. The study identified four (4) areas where sustainability literacy of construction stakeholders is integrated into the UK's social housing construction sector to enhance affordability and sustainability. They are leadership and governance, technology and technical skills, collaboration and knowledge sharing, and user-centric approaches. The findings become significant in embedding and strengthening stakeholders' sustainability literacy in the above identified areas to enhance sustainable features and affordability of social housing construction through stakeholder management as a solution to the current social housing crisis in the UK.*

***Keywords:*** *Sustainability literacy, UK social housing crisis, affordable houses, stakeholder management.*

## 1 Introduction

The social housing sector in the UK is currently undergoing a crisis due to the inability to meet the increasing demand for social housing. As this resulted in increasing homelessness, overcrowding, economic strain, public health and well-being, and many other aspects, attainment of an enduring resolution is mandatory. Booth (2025) stressed the necessity of redefining UK affordable houses as critical infrastructure following the present social housing crisis. For instance, BBC (2024) reported that the current social housing construction projects are on hold due to lack of funds and that existing funds mostly cover the repairing costs of existing social houses. It further disclosed that local councils are bearing expenses of over £1 billion per annum on temporary accommodation, resulting in cash flow issues. Therefore, construction of affordable houses becomes highly significant. In assessing the ways of meeting the increased social housing demand, sustainable construction could be brought to light (Rafa and Khalid, 2024; Alsaeed, 2025; Ellis et al., 2024). This is due to its ability to reduce potential construction and maintenance costs via energy consumption minimization, meeting net zero goals, life cycle costing, project delay mitigation, etc. (ESG Social Housing Working Group, 2020; CEBR, 2023). The applications of sustainable affordable houses range over nature-based vernacular living with low carbon footprints to modern, industrialized buildings (Rincón et al., 2023). Consequently, the present study explores the integrity of sustainability literacy in the UK's sustainable and affordable social housing construction through stakeholder engagement. This research becomes substantial in identifying strategies for overcoming the existing social housing crisis.

## 2 Literature Review

### *Causes and Effects of the UK's Social Housing Crisis*

Identification of root causes of the UK's social housing crisis is noteworthy in developing resolutions (Hagan and Ahmed, 2025). According to Bano (2025), the contributory factors include the dominance of landlords and prioritization of profits in social housing construction, policies that empowered the private rental market over the security of tenants, reduction of social housing stock, and social implications such as homelessness and overcrowding. Consequently, the root causes are the underlying economic and political issues. In assessing the study of Hilber and Schöni (2022), the growing population, income and restraining land-use planning schemes have resulted in generating a demand for affordable housing. Due to the increased demand, the prices ranked high together with the housing shortage. Accordingly, it is recommended to prioritize policy improvements and boost the supply to accomplish affordability. A similar study conducted by Zhang (2025) revealed that housing affordability is severely threatened by shifting towards profit-oriented policies over aspects such as security of tenure, affordability, and housing equality. The scarcity of affordable housing brought on by low incomes and rising living standards is making things more challenging (Momoh et al., 2024).

The research conducted by Dorling (2010) examined the root causes of the UK's social housing crisis from a social perspective. Consequently, prioritization of the financial aspect of housing over social needs affected the social instability. Therefore, this study stressed the necessity of having safe and affordable housing to create a stable and cohesive society. According to Akaiku et al. (2025), one of the main causes of the housing shortage is scarcity of land. While the study revealed that the UK government facilitates off-site construction and brownfield site redevelopment as a sustainable solution for this issue, financial, policy, and technical challenges still exist. Overall, the present social housing shortage could be identified as a combination of social, economic, political, and demographic causes (Pagani et al., 2025).

The study conducted by Pagani et al. (2025) stated the effects of the UK's social housing shortage as higher complexities and management issues associated with housing providers, lack of funds, gaps in policies, and inadequate housing conditions that failed to meet regulations. According to Fee (2025), the current social housing issue is a result of transformations that have been made over the past four decades. Stated differently, a rise in real affordable social housing construction has not resulted from the trend toward privatization and provider diversification. In contrast, the present social housing sector has become more insecure with a breakdown in tenants' rights and equal access to social houses. The growing social housing shortage has generated numerous challenges, such as homelessness and detrimental effects on social mobility, productivity, and well-being for traditional social housing seekers (Hilber et al., 2024). Lo et al. (2024) exposed that the unaffordability of social houses is possible to expand from larger cities to smaller towns, particularly in a thriving economy, stressing the necessity of adapting innovative resolutions to overcome existing challenges.

***The Significance of Enhancing Sustainability Literacy and Stakeholder Engagement in Delivering Affordable and Sustainable Social Housing in the UK***

A set of abilities known as sustainability literacy enables active engagement and control over societal perspectives (Stibbe, 2009). Sustainability literacy is possessing the knowledge, competencies, dispositions, and qualities to make informed decisions for the advantage of everyone involved, both presently and in years to come (Irwin, 2015). Sustainable construction addresses the existing social housing crisis (Rafa and Khalid (2024), Alsaeed (2025)). Yet, it is associated with various challenges. For instance, the National Housing Federation (2022) revealed the importance of decarbonizing social houses, as they are contributing to about 17% of carbon emissions in the UK. This also serves the attainment of affordability, as it reduces energy consumption and improves tenants' well-being. However, the financial constraints, construction skills shortages, and other associated complexities are found to be some of the present challenges in the decarbonization process. In contrast, similar research conducted by Daniel et al. (2024) stated that the necessity of complying with sustainable goals such as energy efficiency and net zero targets increases housing construction costs and complexities associated with them, despite the sustainable outcomes. The study's suggestions for affordable social housing construction include adapting modern construction techniques, enhancing government support, and increasing the borrowing cap for local authorities. Financial, technical, and social constraints are required to prevail for effective decarbonization of social houses (Marshall et al., 2025). However, Hettiarachchi and Atuahene (2023) argued that attainment of decarbonization targets is complex and tough, particularly due to lack of sustainability literacy among the construction professionals. As withstanding the existing challenges of sustainable applications is significant in resolving the social housing crisis, enhancing construction stakeholders' sustainability literacy becomes similarly important. Sustainability literacy should be highly concerned with actively embedding modern construction effectiveness measures such as environmental safety and social equity, in contrast to traditional measures such as efficiency and profits (Murray and Cotgrave, 2007).

Off-site construction and retrofitting are some of the other options for overcoming the existing gaps in the UK's social housing sector via sustainable applications. Both retrofitting and offsite construction minimize the carbon footprint (Pomponi and Moncaster, 2017). According to the analysis of Agapiou (2022), despite the benefits offered by offsite construction, the industry experiences a higher upfront cost, supplier shortage, and resistance to adapting modern technologies in practice. Similarly, Charles et al. (2025) exposed that even if retrofitting improves energy efficiency, it has limitations in addressing underlying issues, including higher energy costs associated with it and equal access to retrofitted social housing. Hence, enhancement of the sustainability literacy of construction stakeholders becomes noteworthy in systematically managing higher costs through innovative resolution. Sustainability literacy helps construction professionals to transform their knowledge and attitudes towards a sustainable future (Cotgrave and Kokkarinen, 2010). According to a study conducted by Xia et al. (2016), promoting sustainability literacy is a valuable approach in bridging the gap between sustainability-related knowledge and knowledge applications in the construction sector. Further, Hettiarachchi (2024) argued that assessment of construction professionals' sustainability literacy in the fields of employment recruitment, innovation, task handover, stakeholder engagement, and leadership is crucial to acquire a considerable contribution towards sustainable construction. Overall, sustainability is instrumental in overcoming existing challenges in the UK's social housing crisis. Enhancement of sustainability literacy of construction stakeholders is therefore important.

***Nature-Based Vernacular Living & Low Carbon Affordable Housing***

Traditional vernacular dwelling provides a promoting example of affordable, sustainable, and carbon-free living. It is anticipated with the use of environmentally friendly materials, supply chains, community engagement and adaptable construction designs and techniques. A study conducted by Mabborang et al. (2022) explored construction of indigenous dwellings in the Philippines and argued that the designs of vernacular houses could be adapted in modern housing construction while preserving culture and heritage. Vernacular housing designs potentially reduce energy consumption and effectively support climate change adaptation (Stanimirovic et al., 2023). Accurate and effective applications of vernacular housing principles benefit not only in attaining sustainability but also affordability (Hugo, 2021). Construction stakeholders' sustainability literacy is a vital factor in adopting vernacular dwelling designs in modern and industrialized construction (Zong et al., 2024). This is because although vernacular architecture is environmentally friendly, social and economic aspects are also required to be considered in attaining sustainable development (Olukoya and Atanda, 2020). Knowledge, skills, attitudes and experience of construction professionals become noteworthy in aligning the objectives of vernacular designs with sustainable goals (Galan et al., 2020).

## 3 Research Problem and Research Aim

The UK's social housing sector struggles to meet the growing demand for social houses within its limited financial capacity. This has resulted in increasing homelessness, overcrowding, economic strain, and public health and well-being. Various scholars discovered sustainable construction to be a resolution to the ongoing social housing crisis due to its ability in positively influencing affordability and sustainable perspectives. Yet, the application of sustainable solutions is still challenging in the construction industry. As sustainability literacy is instrumental in bridging gaps between sustainability-related knowledge and sustainable applications, this research aims at exploring the integrity of sustainability literacy in the UK's sustainable and affordable social housing construction through stakeholder engagement.

## 4 Research Methodology

Systematic literature reviews examine various states of research questions and recommend suitable resolutions to improve (Frank and Hatak, 2014). This study has integrated a systematic literature review that follows PRISMA (2020) guidelines. Integration of PRISMA protocols into systematic literature reviews enables a methodical assessment (PRISMA, 2020). The secondary data, which were published from 2010 to 2025, were gathered through Google Scholar, Taylor and Francis, Emerald Insight, and Science Direct databases. A broad spectrum of sources is interconnected through those sources (Martín et al., 2019; Mamikutty et al., 2021). While Table 01 illustrates data search syntax, the PRISMA flow diagram (Figure 01) was utilized to structure the flow of the literature review. Following the interpretation of Kalocsányiová (2024), this study has defined sustainability literacy as “the knowledge, abilities, and mindsets that encourage someone to profoundly dedicate themselves to creating a future.”

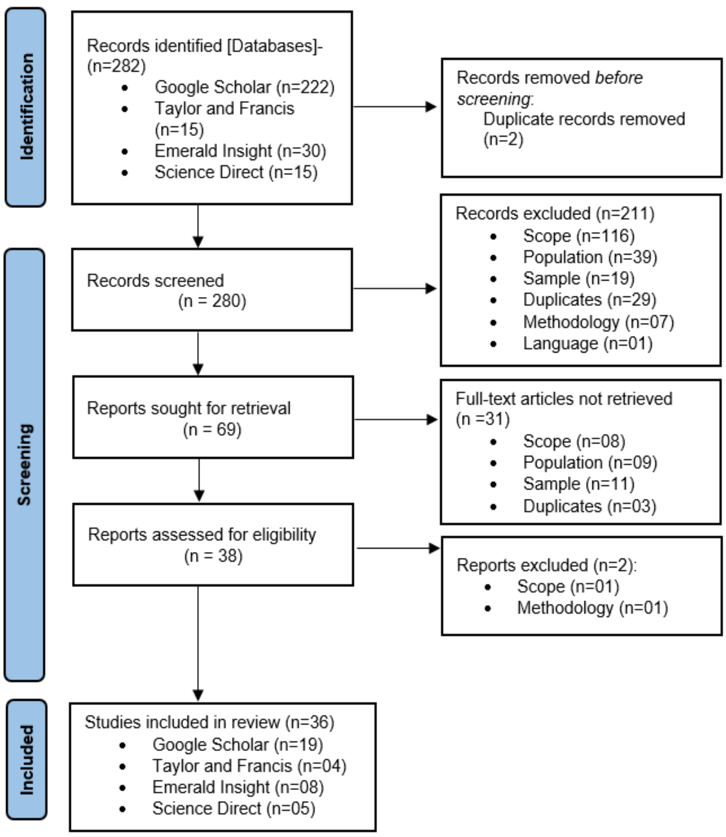


**Figure 1: PRISMA Flow Diagram**

While the "scope" refers to each study's alignment with this research's aim, "population" and "sample" denote housing construction and UK social housing construction respectively. This study excluded repeated records ("duplicates") and included articles published in Engligh only ("language"). In considering research methodology, non-empirical publications and studies that lack clear methodology were excluded within the PRISMA analysis.

**Table 1: Data search syntax of each database.**

| Database | Data Search Syntax |
|---|---|
| *Google Scholar* | *"sustainability literacy" AND "stakeholder engagement" AND sustainability AND "UK social housing"* |
| *Taylor and Francis* | *[All: "uk social housing"] AND [[All: sustainability] OR [All: "sustainability literacy"]] AND [All: stakeholders] AND [All Subjects: Built Environment]* |
| *Emerald Insight and ScienceDirect* | *"UK social housing" AND ("sustainability" OR "sustainability literacy") AND (stakeholders OR "stakeholder engagement")* |

## 5 Data Analysis

The systematic literature review discovered four (04) main categories where sustainability literacy of construction stakeholders is integrated into the UK's social housing construction sector to enhance affordability and sustainability. They could be classified as leadership and governance, technology and technical skills, collaboration and knowledge sharing, and user-centric approaches.

### *5.1. Governance and Leadership*

According to Kaluarachchi (2015), attributes of sustainability literacy such as knowledge sharing, practice and training, effective communication, skills transfer, and avoidance of resistance to change are required to be embedded into leadership in promoting sustainable social housing construction in the UK. Similar research conducted by Pagani et al. (2023) emphasized the necessity of including systematic governance and sustainability-related perceptions into social housing construction. It argued that construction stakeholders should establish a "responsible generation," which generates accountable mindsets using innovative and systematic thinking, acquisition of broader knowledge areas, skills and competencies, and empowerment towards sustainable social housing in England. The need for changing traditional mindsets, knowledge sharing, and effective collaboration in sustainable social housing construction is critical in the present, not only to achieve sustainable goals but also to attain affordability (Rodger et al., 2020). As sustainability and innovation are least prioritized in the UK social housing repair and maintenance projects, construction professionals' leadership is required to address this issue (Tucker et al., 2014). In addition, sustainability should be embedded into asset management of social houses in the UK to maximize their value within a limited cost, especially considering the rising social housing demand (Opoku et al., 2018).

In assessing the aspect of governance, Lizarralde et al. (2015) argued that UK government policies and frameworks are subject to the impact of tensions, and therefore "sustainability" and "resilience" are sometimes misinterpreted in practice. Therefore, the authors have exposed the importance of constructively integrating both above concepts through policy and framework development to address existing gaps in sustainable applications. Similarly, Shaw and Ozaki (2013) revealed that some UK environmental policies failed to reflect that sustainable practices mean not only policy implementation but also embedding sustainable technologies in professional practice. Following both above studies, it is clear that an accurate definition of “sustainability” and “sustainability literacy” is useful for construction stakeholders to improve sustainable practices. Moreover, Hawkey et al. (2013) highlighted the necessity of encouraging stakeholders to collectively uphold government policies on District Heating and Cooling (DHC) systems for sustainable energy sourcing. It includes overcoming the existing challenges associated with a centralized energy market, high capital cost, primitive supply chains, and declined community bonds. Enforcement of sustainable development policies is essential in procuring social housing projects, as only a limited number of organizations have developed sustainable development policies and integrated all core aspects of sustainability (i.e., environmental, social, and economic) so far (Carter and Fortune, 2007). Overall, stakeholders’ integration is significant in embedding sustainability literacy through leadership and governance in the UK’s social housing sector.

### *5.2. Technology and Technical Skills*

The difficulties faced by stakeholders in social housing construction are lack of sustainability literacy, prioritizing finance over quality, insufficient assessment tools, insufficient institutional support, and loops of existing toolkits (Higham, 2014). Hence, enhancement of professionals’ technical literacy is important for overcoming existing gaps in energy performance in the UK’s social housing projects (Alencastro et al., 2020). Construction stakeholders’ skills and awareness of net-zero buildings are timely and essential to address gaps of uncertainty of practices and in boosting consumer confidence (Okonta and Rahimian, 2024). According to Narula and Finnegan (2025), technical skills are vital in adopting LGSF (Light Gauge Steel Frame) modular housing, which is a sustainable approach for achieving net-zero goals in the social housing sector. Sustainability also improves affordability by empowering energy performance, and professionals’ technical skills are crucial in it (Forde et al., 2020, Brown and Gee, 2024).

Even though the construction professionals’ general sustainability literacy levels are adequate in the UK, technical skills development is required, as implementation consists of a few gaps, including lack of sustainability models, toolkits, and frameworks adoption and misinterpreted perceptions of energy efficiency and life cycle management (Higham et al., 2016). Skills in identifying needs, effective project planning, and post-contract inspection are essential in achieving affordability through efficient social housing maintenance (Sharp and Jones, 2012). According to Phillips and Forman (2018), lack of understanding of BIM and associated other technologies is a major disadvantage in social house retrofitting. Hence, education, awareness, and skills in BIM and other modern technologies should be developed to overcome the identified challenges. (Phillips and Forman, 2018; Phillips and Streatfield, 2019; O’Malley et al., 2014). Gangolells et al. (2021) discovered the synthesis of gamification for different energy efficiency models to be a successful adoption for strengthening user engagement and reducing energy consumption. Overall, technology and technical skills facilitate sustainability literacy integration in sustainable and affordable social housing projects (Baba et al., 2012).

### *5.3. Collaboration and Knowledge Management*

According to the analysis of O'Malley et al. (2014), sustainability literacy is actively integrated among both internal and external stakeholders in the UK's social housing sector. However, the study argues that knowledge sharing, and collaboration are still needed to successfully adopt sustainability assessment methods such as CSH, LEED, and CASBEE. Sustainability literacy is a critical factor, as construction professionals are liable to implement target settings, commencement, monitoring, and evaluation to reduce carbon emissions throughout their supply chains using collaboration and knowledge sharing in social housing construction (Gupta et al., 2015). In terms of retrofitting social housing, integrated collaboration between resident stakeholders and high-level stakeholders is required to further develop by considering social values and occupants' needs. (Furman and Hadjri, 2025). According to Mensah and Ameyaw (2025), internal stakeholders' (i.e., contractors and consultants) awareness of social value Integration for sustainability through procurement could be enhanced via education, awareness, skills, and training to fully integrate the concept of sustainability in the social housing sector. Meehan and Bryde (2015) revealed that most housing providers are committed towards sustainability and sustainability literacy to a certain extent, as positive attitudes on sustainable applications, strong aptitude in collaborative procurement, and housing occupants' high preference in dealing with sustainable procurement matters were identified. However, the authors stress that regulators' expertise in sustainable procurement is inadequate and therefore recommend effective collaboration among the UK's housing associations and supply partners for sustainable procurement. Leblanc et al. (2010) noted that effective communication and knowledge transfer are required to be developed among construction stakeholders to attain practical sustainable goals in the social housing sector through sustainability literacy advancement. It is also useful in long-term asset management (Cooper et al., 2020). According to Phillips (2017) and Rodger et al. (2020), stakeholder collaboration is vital not only in improving sustainable aspects but also in developing affordable social houses via effective cost management.

### *5.4. User-centric Approaches*

Various studies argue that sustainability integration does not entirely rely on construction professionals but also on building occupants/tenants, as projects attain clients' needs at the end. Therefore, sustainability literacy attributes such as tenants' up-to-date knowledge, awareness, and attitudes are important, as they define the degree of sustainability of social housing projects (Morgenstern et al., 2015). According to Cauvain and Karvonen (2018), tenants require education on energy-conserving methods that could be implemented through energy consultants and residential visits. Tenants' knowledge, skills, and communication are highly beneficial in implementing renewable heating technology in social houses (Moore et al., 2015). As technology is generally embedded into sustainable social housing, end-users' skills and knowledge development should be prioritized in all environmental, social, and economic aspects of sustainability (Morgenstern et al., 2015). It is timely and fundamental, as Sunikka-Blank et al. (2018) revealed less privileged tenants to be experiencing difficulties in adapting to new technological applications. Research conducted by Morgan et al. (2024) discovered that tenant agencies often exclude elderly building occupiers and those who are experiencing financial hardships. Similarly, the level of understanding of residents' values varied among different professionals/stakeholders. While the study also stressed that community involvement of tenants improves sustainability aspects of social housing projects, it exposed that stakeholders' support is highly inadequate in this process. Considering the above three factors, Morgan et al. (2024) recommended providing a user-centric approach by educating tenants and closely linked stakeholders on sustainability and digital skills. Similarly, Gupta and Chandiwala (2010), Gupta et al. (2015), and Morgan et al. (2024) suggested obtaining feedback from the building occupiers in resolving matters timely.

**Table 2: Integrity of Sustainability Literacy in the UK's Social Housing Construction Sector**

| ***Category*** | ***Integrity Sectors*** |
|---|---|
| *Governance and Leadership* | • *Systematic governance and sustainability awareness.*<br>• *Mindset change, collaboration, and affordability.*<br>• *Leadership focus on sustainability and innovation in maintenance projects.*<br>• *Policy and framework development for sustainability and resilience.*<br>• *Stakeholder alignment with government sustainable energy systems.*<br>• *Enforcement of sustainable development policies in procurement.* |
| *Technology and Technical Skills* | • *Technical literacy of construction professionals.*<br>• *Skills and awareness of net-zero buildings and net-zero goals.*<br>• *Sustainability models, toolkits, and frameworks.*<br>• *Synthesis of gamification for different energy efficiency models.* |
| *Collaboration and Knowledge Management* | • *Sustainability assessment methods*<br>• *Target settings, commencement, monitoring, and evaluation to reduce carbon emissions.*<br>• *Sustainable procurement.*<br>• *Stakeholder collaboration, effective communication and knowledge transfer.* |
| *User-centric Approaches* | • *Tenant sustainability knowledge, awareness, attitudes including energy conserving practices and renewable heating use.*<br>• *Proficiency in technology use.*<br>• *Community involvement of tenants.*<br>• *Feedback collection from building occupants.* |

## 6 Conclusion and Recommendations

Even if sustainability literacy is crucial in promoting both sustainability and affordability in social housing construction, practical implementation is found to be challenging. While most data indicated integration of sustainability literacy towards sustainability, only limited data examined its impact on affordability. Therefore, this study builds upon prior research demonstrating that sustainable construction practices contribute to lowering potential construction and maintenance costs via energy consumption minimization, meeting net zero goals, life cycle costing, project delay mitigation, etc. (ESG Social Housing Working Group, 2020; CEBR, 2023). The study identified four (4) areas where sustainability literacy of construction stakeholders is integrated into the UK's social housing construction sector to enhance affordability and sustainability. They are leadership and governance, technology and technical skills, collaboration and knowledge sharing, and user-centric approaches. Hence, the study recommends strengthening the sustainability literacy of construction stakeholders in those identified areas to overcome challenges faced during the current social housing crisis in the UK. Accordingly, leadership and governance could be enforced by embedding sustainability literacy into leadership roles and government/organizational policies to foster practical commencement. It includes developing leadership traits and accurate integration of sustainability in policy development. Technical skills of construction stakeholders are also required to be improved to overcome the gaps in continuous development and equal adaptation. It could be done by enhancing sustainability literacy and technical literacy. Collaboration and knowledge sharing remain essential for further developing the existing sustainability assessment methods, supply chains, and sustainable procurement. User-centric approaches demonstrate the necessity of prioritizing clients' needs and enhancing their sustainability literacy and technical competencies to gain long-term benefits of sustainable and affordable social housing construction. The establishment of mechanisms to obtain and monitor feedback is an effective user-centric approach. The identified categories disclose areas to consider in improving sustainable and affordable perceptions in the UK's social housing sector. In addition, sustainability literacy of construction stakeholders becomes beneficial in aligning the key objectives of vernacular designs with sustainability goals of modern construction.

## 7 Limitations and Further Study Directions

The present study was based on a qualitative analysis, meaning further studies are open to conduct following quantitative and mixed methods. Accordingly, data could be gathered through primary data sources and via secondary databases other than Google Scholar, Taylor & Francis, ScienceDirect, and Emerald Insights. As the present study's data were published between 2010 and 2025, further research can focus on another timeframe. The research published in English was only considered in the systematic literature review. Hence, relevant articles published in other languages could be considered in the future. As this research was developed based on a systematic literature review, generalization of research findings became challenging. The study also follows the definition of sustainability literacy of Kalocsányiová (2024). Therefore, further studies could integrate different dimensions of sustainability literacy.

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# BIO-BASED INSULATION MATERIALS FOR RURAL HOUSING RENEWAL: CHALLENGES AND OPPORTUNITIES

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***Abstract:*** *Rural areas face multiple challenges, including ageing housing, insufficient insulation, and energy inefficiency, which affect the well-being of residents and constrain the low-carbon transition. Despite the increasing coverage of rural areas by green building policies, the application of local biomass resources for energy-efficient retrofit of rural housing is still not systematically explored. This study conducted a comparative analysis of eight representative peer-reviewed studies published between 2015 and 2025, covering four climatic zones and two structural typologies, to assess the applicability of bio-based insulation materials in the retrofit of old rural houses. The analysis focused on their thermal performance, life cycle carbon reduction potential, and suitability for construction implementation. It was found that bio-based materials such as straw, hemp, and wood fiber exhibit significant advantages under localized purchasing and modular prefabrication conditions, but face challenges such as durability validation, lack of flame-retardant properties, and space constraints. Although preliminary modularization paths have been proposed, technical standards and sustainable construction mechanisms have not yet been established. In this paper, we emphasize the need to promote locally adapted and cycle-oriented building retrofit solutions from the perspectives of structural suitability, supply chain synergy, and policy incentives, and to transform bio-based prefabricated systems into a low-carbon regeneration strategy for rural areas.*

***Keywords:*** *Rural Housing; Bio-based Insulation; Prefabrication; Circular Construction; Low-carbon Retrofit*

## 1 Introduction

In the context of the global “Peak Carbon - Carbon Neutral” strategy, building energy efficiency retrofit is regarded as one of the paths with the greatest potential for emission reduction. Liu et al.'s (2025) bibliometric analysis shows that the number of publications related to “building renovation + carbon neutrality” has increased dramatically after the Paris Agreement, accounting for nearly one-third of the hot topics in building emissions reduction research. The CRREM report by Bienert et al. (2023) further estimates that the implementation of deep energy efficiency renovations in existing buildings could result in cumulative reductions of approximately 40 Gt CO2e by 2050, highlighting the strategic value of retrofitting older buildings to achieve net-zero goals.

In this context, the energy efficiency of buildings in rural areas is particularly problematic. (According to the EU’s DEGURBA classification, rural areas refer to thinly populated areas where more than 50% of the population lives in rural grid cells—defined as grid cells not classified as urban centres or clusters.) Their energy performance is even more unfavourable due to the envelope's general age and low thermal performance. In a systematic review, Abouaiana and Battisti (2023) pointed out that studies in the last decade have agreed that rural houses in “high altitude and inaccessible” areas generally lack effective insulation measures.

Most cases of rural building retrofit still rely on “post-modern” traditional insulation materials such as mineral wool or polystyrene boards, and their carbon emissions from manufacturing and long-distance transportation can account for more than 70% of the overall embodied carbon emissions of deep retrofit projects (Bienert et al. 2023). Meanwhile, a review by Lisowski and Glinicki (2025) shows that local agricultural and forestry residues such as rice straw, rice hulls, and wheat straw exhibit thermal conductivity of $\leq 0.100\ W \cdot m^{-1} \cdot K^{-1}$ but still remain as “potential materials” rather than having reached mainstream market status. The latest scenario analysis from the Bio-based Industries Consortium (Carus et al. 2025) further estimates that the on-site exploitation of these agricultural by-products could meet more than 20% of Europe's carbon demand for building materials by 2050, although a specific pathway for the retrofit of old rural houses has not yet been established.

Although growing attention has been paid to bio-based materials in the building sector, existing studies remain fragmented across different climatic regions and building typologies, and few have systematically compared their performance and feasibility in the specific context of rural housing renovation. Moreover, the integration of circular design principles—such as modularity, reversibility, and localized material reuse—has rarely been addressed within this research domain. To fill these gaps, this study systematically evaluates the applicability of bio-based insulation in the energy-efficient renovation of existing buildings in rural areas through a literature review. It focuses on the potential of bio-based insulation to improve building energy performance and thermal comfort, as well as the key constraints in material performance, construction implementation, and dissemination pathways in current practice. The study aims to provide theoretical and practical references for green renovation technologies based on local resources, and to promote the development of low-carbon building retrofit strategies applicable to rural areas.

### *1.1 Policy and technical context for retrofitting rural buildings*

Existing dwellings in rural Europe are generally thermally weak and energy-intensive. According to the European Commission Joint Research Centre (JRC), rural dwellings are often "larger, older and less energy efficient", making rural dwellers more vulnerable to energy poverty than urban dwellers (European Commission Joint Research Centre 2025, Özdemir and Koukoufikis 2025). In Italy, official statistics show that 54% of rural houses were built before 1971 and 14% of them still rely on solid fuels for heating, resulting in high heating bills and greenhouse gas emissions (ISTAT - Rural Energy Italy 2024); The situation in the UK is equally dire: the Fuel Poverty Monitoring Report 2023 estimates that 6.7 million households are in fuel poverty, with the lack of insulation in older rural homes being a major contributing factor (Department for Energy Security and Net Zero 2023).
To reverse this situation, the EU Energy Efficiency in Buildings Directive (EPBD 2010/31/EU; EPBD 2024/1275/EU) requires Member States to achieve cost-optimized minimum levels of energy efficiency in "major refurbishments" of old buildings and to develop a roadmap for long-term refurbishments. In Italy, tax credits such as Eco-bonus and Super-bonus 110% provide tax incentives of 50-110% for expenditures on retrofits such as envelope insulation, renewable heating systems, etc., to promote at least a two-stage improvement in the energy efficiency rating of older homes (Macchiaroli et al. 2023).

### *1.2 Development Status and Advantages of Bio-Insulation Materials*

The current incentives focus on traditional mineral wool or polystyrene systems, and the use of bio-insulation in building renovation is not yet widespread. In the construction industry, bio-insulation materials are defined as building products containing plant or animal biomass; as such, they are made from renewable raw materials, often derived from by-products of agriculture or the wood industry. Numerous experiments have shown that such materials possess a hygroscopic macroporous network that combines high water vapor permeability with moisture buffering capacity, giving them an inherent ability to regulate indoor humidity (Rahim et al. 2017). Common bio-based insulation materials include rice straw, hemp shavings or hemp-lime, wood fiber, flax, wool, and rice husk panels. Dry thermal conductivity is generally reported to be between 0.030 - 0.070 W $m^{-1}$ $K^{-1}$ (Collet and Pretot 2014), making them comparable to mineral wool in terms of performance but with lower energy consumption. Recent reviews have shown that bio-based materials have been used in load-bearing blocks, infill and plaster, but the most mature marketed products are factory prefabricated exterior wall insulation panels that serve building envelope retrofit by virtue of their lightweight and vapor-openness advantages (Bourbia et al. 2023). Figure 1 illustrates the closed-loop value chain envisaged in this study—from crop cultivation and harvest of cereal residues, through their conversion into prefabricated insulation components for ageing rural dwellings, to their end-of-life recovery via disassembly and composting.

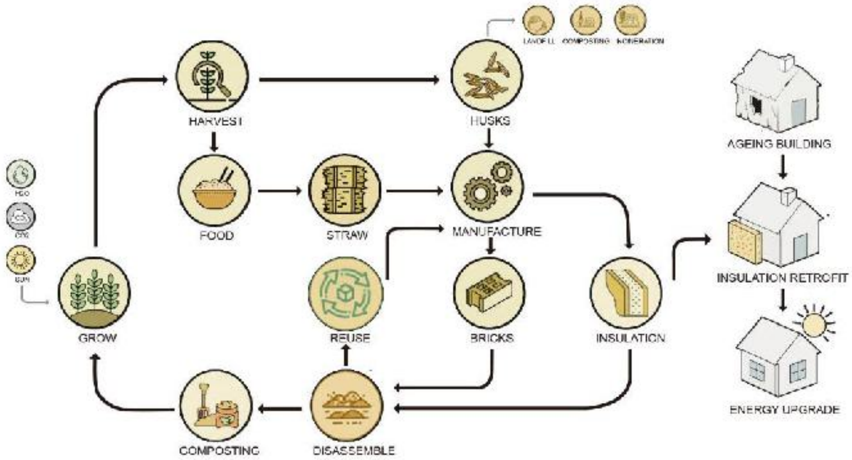


**Figure 1: Circular material flow of straw-based bio-insulation for rural building retrofit. Source: Author self-painted**

On the resource side, biomass is sufficiently accessible. EU countries can produce about 419 Mt (dry weight) of crop straw and stalks per year, of which wheat alone contributes 155 Mt (García-Condado et al. 2019). In the Po River Basin in Italy, where rice farming spans approximately 230,000 hectares and generates about 1.6 Mt of rice annually, rice husks and straw—typically harvested and processed together—have been utilized by local enterprises (e.g., Ricehouse) to produce prefabricated bio-based insulation panels due to their silica-rich properties (Pej and Streibel 2024). Life Cycle Assessment (LCA) also shows significant emission reduction potential. In Northern Italy, Carcassi et al. (2019:237-247) calculated that the use of local wood with hemp cores instead of mineral envelope products could sequester about 140 kg $CO_2$ eq $m^{-2}$ over the life cycle of the building; Similar findings have been made in Central Europe: Vanova et al. (2021) report that straw bale load-bearing walls in Slovakia reduce the combined environmental impact by 60% compared to traditional masonry walls.

## 2 Methodology

This study is a structured literature review on the use of bioinsulation in building renovation, focusing on assessing its applicability and research gaps in rural housing. The study aims to systematize current technological and methodological advances in the subject, identify key challenges, and reveal knowledge gaps at both academic and practical levels. While not intended to be exhaustive, this paper seeks to provide a representative and analytical perspective to support future research and policy development.

We used the Scopus database to develop a sub-topic search strategy, focusing on the following three core dimensions:

1) Construction object: Covering walls, enclosure panels, and building bodies in the building envelope.
2) Material categories: Focus on natural or bio-based insulation materials such as straw, wood fibers, hemp, hemp-lime, biocomposites, etc.
3) Application Context: Focus on energy efficient retrofit practices for rural housing, mountainous built environments, vernacular buildings and existing buildings in remote areas.

The main search terms used are: *TITLE-ABS-KEY ( "bio-based insulation" OR "natural insulation" OR "natural material*" OR "bio-based material*" OR "bio-composite*" OR "straw" OR "wood fiber" OR "hemp" OR "hempcrete" OR "hemp-lime" ) AND TITLE-ABS-KEY ( "building*" OR "house*" OR "wall" OR "envelope" OR "panel" ) AND TITLE-ABS-KEY ( "rural" OR "mountain area" OR "vernacular" OR "remote region" ) AND ALL ( retrofit* OR renovat* OR refurbish* OR "building upgrade" OR "energy efficiency" )*

In this study, literature selection was limited to peer-reviewed journal articles and conference proceedings published between 2015 and 2025, a ten-year span chosen to capture the surge of research on bio-based construction materials following the 2015 Paris Agreement and the increasing emphasis on circular economy strategies across Europe. The initial search yielded a total of 88 publications, which were subsequently selected for relevance by reviewing the titles, abstracts and selected full text. Some of the literature focused on bio-based materials but lacked application contexts in the rural housing context, while other studies focused on life cycle carbon assessment, material performance modelling, or agricultural facilities (e.g., livestock and poultry buildings), and therefore were not included in the final analysis. Eight core publications were selected as highly relevant to the research questions and served as the basis for subsequent comparisons and discussions. [1] Barreca et al. 2019; [2] Speciale et al. 2025; [3] Yin et al. 2020; [4] Charai et al. 2021; [5] Stanimirovic et al. 2023; [6] Costantino et al. 2024; [7] Barreca et al. 2023; [8] Mileto et al. 2021.

Overall, the methodology reveals a limited number of relevant studies but also reflects the fact that the field is still in its infancy. The selected literature provides a basis for analysing the feasibility, bottlenecks and development potential of bio-based prefabricated solutions in rural transformation.

## 3 Discussion

The selected studies generally focus on the energy efficiency, material adaptability and implementation feasibility of bio-based insulation in rural and mountainous housing retrofits, but there are differences in their depth and focus. Most of the literature focuses on thermal performance and energy performance during the practical use phase, a few studies further explore the environmental impacts of the material sources, while only a few cases deal with removability and recycling potential. Despite the different approaches, the authors are consistent in pointing out that material selection and design strategies must be responsive to different climatic zones, building types, and local resource conditions in order to truly utilize the role of bio-based materials in low-carbon retrofits. To this end, the discussion in this paper is organized into three thematic dimensions: (i) thermal performance and energy efficiency performance; (ii) Life cycle carbon footprint; (iii) implementation suitability and practical barriers.

### *3.1 Results*

Table 1 compares the key findings of the selected literature, covering their practical feedback in different regional climates, building types and material combinations, including four climatic zones (cold, temperate, warm-humid, semi-arid) with two types of old building structures (stone/brick masonry, timber frame). They collectively quantify the energy efficiency benefits, whole-life environmental gains, and barriers to implementation, providing multidimensional evidence for the adoption of bio-based insulation for rural retrofits. The following subsections further extract common trends, divergent pathways, and gaps for future depth across the studies.

**Table 1: Comparative analysis of papers on bio-based insulation in rural housing retrofits**

| | **Region / Climate** | **Building typology & Scope** | **Bio-based insulation studied** | **Key findings** | **Gaps identified** |
|---|---|---|---|---|---|
| [1] | Italy – Mediterranean Coast (warm-summer) | Traditional masonry rural house (Mediterranean); exterior wall retrofit | Giant reed panel / agglomerated cork | Giant reed reduces HVAC load by ~56%, cork by ~75%; | Not tested for moisture and flame resistance |
| [2] | Italy – Lombardy (cold-temperate) | Early 20th-c. stone-timber hamlet; full retrofit | Hemp shives, wood chips, waste wool | Natural panel mix achieves "CasaClima A"; net carbon sink; payback <7 yrs | Lacks standardized design tools and on-site logistics design |
| [3] | China – Northeast (severe-cold) | 1950s timber houses; straw-bale infill retrofit | Straw bales + timber | Heating demand reduced 46–204 kWh/m²·yr; coal saving >40% | Hygrothermal control & social acceptance not tested |
| [4] | Morocco – Semi-arid (hot-day / cold-night) | Earthen rural house: roof & wall retrofit | Gypsum + 2–6% hemp fibres | λ drops from 0.53 → 0.36 W/m·K; cooling demand reduced by 4.7% | Unresearched aging and industrialization |
| [5] | Serbia – Mountain (continental) | 19th-c. timber-frame house; full envelope retrofit | Sheep wool / Hemp wool | Heating demand halved; sheep wool lowest $CO_2$ impact | Flame retardant certification and lack of local supply chain |
| [6] | Italy – South (warm-humid) | Interior partition retrofit | Giant reed + gypsum + oleogel Phase Change Material | Heat flux absorption increased 57%; stable at 27.5°C | Limited integration guidelines, durability, and space issues. |
| [7] | Italy – Lazio (humid continental) | Stone masonry house in Valentano; LCA of 12 insulation options | Wood fibre, cork | Wood fibre GWP lowest (8.18 kg $CO_2$ q/m²); operational impact ~90% | Biogenic carbon excluded; lacks reuse & cultural analysis |
| [8] | Spain – Valencia (Mediterranean) | Late-18th c. stone-earth rural house (Sesga); full envelope retrofit | Lime-hemp render, cork board, timber | Traditional retrofit lowest impact in 9/11 indicators | Needs dynamic simulation & socio-economic scaling |

### *3.1.1 Thermal Performance and Energy Efficiency*

In the selected cases, thermal performance enhancement during the use phase of the building is the most concentrated research focus, especially in cold and temperate regions. Yin (2020) showed through a combination of simulation and real measurements that a straw bale infill refurbishment scheme in the Northeast can reduce annual heating demand by 46-204 kWh/m² and coal consumption by about 40%, showing significant energy saving potential. In the Serbian mountains, Stanimirović et al. (2023) achieved the result of halving the heating load of a 19th-century timber-framed house using 100 mm thick insulation boards made of wool and hemp fibers. In the Mediterranean and semi-arid climate zones, the focus of the research shifted to the assessment of summer overheating and peak regulation capacity. Charai et al. (2021) reduced the roof thermal conductivity from 0.53 to 0.36 W/m-K in Morocco by incorporating 6 wt % of hemp fibers in gypsum, reducing the cooling load by 4.7%, while Barreca et al. (2023) utilized composite panel walls constructed from PCM and reeds to increase the peak heat absorption by 57% in tests in southern Italy. 57% and effectively moderated diurnal temperature fluctuations. In summary, bio-based insulation materials show differentiated advantages in different climate zones: fibre-based materials are better suited for heating-dominated zones, while composites that are thermally inert or have thermal storage capacity are better suited for cold-load control and day-to-day fluctuation mitigation.

### *3.1.2 Life cycle carbon footprint*

Although not all literature performs a full life cycle assessment (LCA), studies have been conducted to show that bio-based materials offer significant advantages in reducing whole-life carbon emissions. Flexible wood fiber insulation boards evaluated by Costantino et al. (2024) have a carbon footprint of only 8.18 kg $CO2$-eq/m² at the production stage, which is much lower than conventional mineral wool with foamed polymer boards. Speciale et al. (2025), by comparing multiple combinations of Lombardy village cases, point out that locally prefabricated panels containing hemp chips, wood chips, and wool not only achieve net biocarbon storage, but also satisfy the CasaClima A energy efficiency standard in Italy and pay back the initial investment within seven years. Mileto et al. (2021) applied a combination of lime-hemp plaster and cork boards in the Sesga House project, reducing the whole-life environmental impact by about 80% compared to industrialized systems. However, Barreca et al. (2019) point out that in high heating zones, operational energy consumption accounts for 85-90% of the carbon footprint over the 60-year assessment period, suggesting that energy efficiency performance is more critical to the total carbon reduction contribution. Therefore, in climate scenarios with high operational energy consumption, energy efficiency performance should be prioritized, while in Mediterranean-type climates with relatively low energy consumption, low ash energy and high biocarbon storage potential become the dominant factors for material selection.

### *3.1.3 Implementation suitability and practical barriers*

In addition to thermal and carbon performance, the practical promotion of bio-based insulation materials is constrained by multiple factors such as material availability, construction adaptability, and long-term performance. Speciale et al. (2025) and Stanimirović et al. (2023) both highlight that the supply of locally sourced raw materials—such as wool, hemp shives, and wood chips—is subject to seasonal limitations and lacks standardized collection and preprocessing protocols, which can significantly increase construction uncertainty and costs, particularly in remote rural settings.

In terms of construction integration, internally applied insulation systems (e.g., wool boards or gypsum–hemp fibre boards) commonly increase wall thickness by up to 40–60 mm, which raises the issue of compressing usable interior space in rural houses with limited depth. This drawback becomes particularly relevant in historic rural settlements, where traditional stone masonry walls are thick and irregular, and residents tend to preserve the original appearance of façades for cultural or heritage reasons. Consequently, external insulation systems are often rejected by local communities or restricted by conservation regulations. While externally applied bio-based insulation systems—such as wood fibre or reed-based ETICS—can effectively improve thermal performance without reducing indoor space, they frequently face aesthetic and approval barriers in protected building areas (e.g., the Sesga House case) (Mileto et al. 2021). These challenges highlight the need for design and policy solutions that balance thermal efficiency with architectural authenticity and spatial usability in rural renovation projects.

Another persistent challenge concerns the durability and safety of bio-based materials. Long-term performance, fire resistance, and ageing behaviour are still only partially documented. Most available experiments are restricted to short-term hygrothermal or small-scale tests, which do not account for the combined influence of moisture, freeze–thaw cycles, biological activity, or UV exposure typical of rural environments. The Phase Change Material (PCM) -reed composites studied by Barreca et al. (2023) have only completed 28 days of indoor simulation testing, which is far from covering the environmental stresses that they may experience during their life cycle. Similarly, fire safety evaluations are often incomplete or inconsistent with harmonised standards, reducing confidence among designers, authorities, and end users.

Notably, part of the literature proposes prefabricated modular design of products such as reed/cork insulation boards with wood fiber ETICS (Barreca et al. 2019, Costantino et al. 2024), which not only improves construction efficiency, but also provides a direction for removable, replaceable and recyclable building components in the future, with strong system upgrade Potential. These implementation issues also reflect a broader need to integrate circular economy principles—such as modularity, reversibility, and material recovery—into retrofit design, which remains an underexplored dimension in current rural housing practices. Also, without more robust long-term data and clearer implementation frameworks, the large-scale adoption of bio-based insulation in rural renovation projects will likely remain limited.

## 4 Future research suggestions

Future research should be based on the existing results and vacancies and systematically promoted around four main lines: durable safety verification - modular integration - circular economy coupling - policy and financial support.

Tests on long-term durability and flame-retardant systems must be complemented. Most cases only give 28-90 days of indoor cycling data (Barreca et al. 2023), which is far from covering the effects of high humidity, freeze-thaw and pest environments in rural areas on fibers such as straw, wool, reed, etc. It is recommended to build a platform for ≥5 years of in-situ monitoring, and to conduct fire-responsive rating tests in accordance with EN 13501-1/GB 8624 (Stanimirović et al. 2023). Stanimirović et al. (2023) synchronize the development of bio-based flame-retardant coatings or mineral encapsulation technologies to balance low toxicity with disassembly and recyclability.

The assembly-modularization pathway deserves focused investment. Reed/cork lightweight panels and wood fiber ETICS have demonstrated the feasibility of factory prefabrication and on-site clamping (Barreca et al., 2019; Costantino et al., 2024). Comparative demonstrations should be constructed in both cold and hot and dry climates to quantify installation time, labour costs, and thermal bridge control, and to explore "reversible connectors + dry moisture barrier" options to set the technical standard for future phased refurbishment or component upgrades.

Regionalized supply chains and circular economy pathways need to be assessed in an integrated manner. Seasonal output of raw materials, collection radius and local processing capacity will directly affect the cost and carbon intensity of bio-based insulation projects in rural areas (Speciale et al. 2025; Stanimirović et al. 2023). Future research should integrate regional data on the supply of agricultural and forestry by-products (e.g., rice husk, wheat straw, hemp stalks, etc.) in both the spatial and time dimensions, and at the same time, combine the transportation network and the layout of processing facilities to establish a feedstock supply model tailored to local conditions. In addition, the environmental and economic benefits of recycling pathways for end-of-life panels (e.g., composting, calorific value utilization, and reforming) should be further assessed in different regions to promote the formation of a local recycling system that places equal emphasis on closing the resource loop and the carbon loop. This will help ensure the sustainability of material use and enhance the feasibility of its application in remote rural environments.

Carbon removal and disassembly technologies at the end-of-life stage remain a blind spot. Only a few LCAs are discussing bio-carbon reuse in Module D (Costantino et al. 2024); there is a need to benchmark fiberboard composting, thermo-electric conversion, and recycling scenarios of recycled boards, as well as to develop low-energy thermo-mechanical decoupling technologies for recycling composite boards containing glue.

Finally, policy-financial coupled incentives are indispensable. It is recommended that bio-based renovation be included in residential energy efficiency subsidies in high-energy cold zones, with graded incentives based on carbon storage + energy savings; and that dual certification of facade suitability + carbon storage be introduced in cultural heritage zones (Mileto et al. 2021). The challenge of approving facades and recovering funds will be solved. Only with the synergistic promotion of scientific research, industry and governance can bio-based insulation materials move from demonstration to a scaled-up, standardized path of low-carbon rural transformation.

## 5 Conclusion

This review is based on eight recent high-quality studies aimed at assessing the feasibility of bio-based insulation in rural and mountainous housing retrofits. The research evidence focuses on three key points. First, when sourced locally and adapted to the local climate, e.g., straw, wool, hemp shavings, wood fiber, and cork, they can significantly reduce heating or cooling loads and enhance indoor comfort. Fiber-based panels perform well in colder, heating-dominated areas, while more thermally inert composites (such as reed phase change material panels) perform better in warmer or diurnal climates because they dampen peak loads. Second, life cycle assessments consistently show that bio-based products have a low implied carbon footprint; some panels even act as net carbon sinks. However, operational energy still dominates total Greenhouse Gas (GHG) emissions in very cold regions, highlighting the need to synchronize improvements in envelope performance and system efficiency. Third, large-scale applications are constrained by supply chain fragmentation, limited durability and fire safety data, thick linings that take up a lot of interior space, and regulatory constraints on historic building envelopes. Aspects of the circular economy-demolition, reuse, or organic recycling-remain marginal in current research, suggesting a significant knowledge gap. Encouragingly, factory-manufactured, dry-installed solutions (e.g., reeded cork cladding, wood-fiber exterior insulation systems) show good constructability and may shorten on-site construction durations.

In summary, bio-based insulation offers a viable strategy for improving the energy and environmental performance of rural buildings. However, their successful application depends on the full integration of materials science, building design, supply logistics and policy frameworks. Future work should prioritize durability testing, modular building innovations, localized life cycle assessment models, and inclusive policy mechanisms to unlock the full potential of nature-based solutions in the low-carbon rural transition.

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# FABRICATION AND CHARACTERIZATION OF NATURAL FIBRE-HYBRID COMPOSITES FOR SMART VILLAGE INNOVATIONS

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**Abstract:**

*Due to their commendable mechanical properties and high strength-to-weight ratio, composite materials are currently in high demand. This study focuses on the development of a new hybrid particulate composite material composed of coconut fibre, polyester resin, and magnesium hydroxide. The fibre selected is coconut fibre. Coconut fibre, used as the reinforcing material, offers several advantages, including low density, biodegradability, recyclability, affordability, and renewability, making it an ideal choice for polymer composites. Polyester resin serves as the matrix material. To enhance the fire-resistant properties of natural fibre-reinforced composites, magnesium hydroxide is added as a filler. The composite material is fabricated using the hand layup method. Mechanical properties such as tensile strength, compressive strength, impact resistance, and flammability are evaluated through standardized testing.*

***Keywords:*** *Composite materials, Coconut fibre, Mechanical properties*

# 1 Introduction

In recent decades, composite materials, plastics, and ceramics have emerged as the predominant materials in the field of engineering. These materials have significant growth in their utilization, branching out into new markets and applications. While composite materials have already demonstrated their worth by offering weight-saving advantages, the current challenge lies in enhancing their durability under harsh conditions and optimizing their cost-effectiveness. This challenge has spurred the development of innovative techniques within the industry.

The introduction of novel polymer resin matrix materials and high-performance fibers such as glass, carbon, and aramid has further broadened the scope and adoption of composite materials. These advancements have also led to noticeable cost reductions. Composite materials are now employed across a diverse spectrum of applications, including the design of composite armor for blast resistance, wind turbine blades, industrial shafts, natural gas vehicle fuel cylinders, paper manufacturing rollers, and even structural support beams for bridges. Additionally, composites are instrumental in retrofitting existing structures to enhance their seismic resistance or repairing damage resulting from seismic events.[1]

The choice of composite materials for a specific application is contingent upon various factors, including the desired service life, complexity of the product's shape, production volume, cost considerations, and the expertise and skills of the designer in harnessing the full potential of composites. In summary, composite materials have assumed a pivotal role in engineering due to their lightweight attributes and versatility. Nevertheless, ongoing endeavours are centered on elevating their resilience and cost-efficiency, with constant innovation and material selection being critical components of this evolution.[1]

A village is a small rural community, larger than a hamlet but smaller than a town. When such a village is equipped with modern technologies while preserving its natural environment, it is referred to as a smart village. The concept of smart villages has been adopted by national, state, and local governments in India as a holistic approach to rural development, inspired by Mahatma Gandhi’s vision of the ideal village and the principle of village self-governance[25].

India is home to approximately 610,010 villages, of which 112,510 are considered underdeveloped. This highlights the need to design and transform these areas into smart villages. With increasing urbanization and modernization, many people migrate to cities in search of better education, employment, and amenities. However, villages play a critical role in the nation’s overall development. Therefore, it is essential to develop villages into self-sustaining communities that provide essential services, employment opportunities, and strong connectivity to the rest of the world — in essence, making them smart villages [25].

### Role of Composite Materials in Smart Villages

**Composite materials**—made by combining two or more materials with different properties—are increasingly used in Smart Village development due to their **strength, durability, lightweight, and corrosion resistance**.

Key Uses of Composite Materials in Smart Villages*:*

| Sector | Application of Composite Materials | Benefits |
|---|---|---|
| Construction & Housing | - Composite roofing sheets (e.g., FRP, CFRP)<br>- Prefabricated modular homes<br>- Fiber cement boards for walls | - Lightweight, durable, low maintenance<br>- Faster and cheaper construction<br>- Weather and termite resistant |
| Sanitation | - Composite toilets (portable, bio-toilets)<br>- Septic tanks made of polymer composites | - Rust-proof, longer life<br>- Easy to install and relocate |
| Water Supply & Storage | - Composite water tanks<br>- Pipe systems made of fiber-reinforced plastic (FRP) | - Leak-proof and corrosion-resistant<br>- Lightweight and easy to install |
| Renewable Energy | - Wind turbine blades made of glass/carbon fiber composites<br>- Solar panel frames | - High strength-to-weight ratio<br>- Increased energy efficiency |
| Transport & Infrastructure | - Composite bridges and walkways<br>- Rural road reinforcements | - Longer lifespan, reduced maintenance<br>- Suitable for remote locations |
| Agriculture | - Greenhouses using composite frames<br>- Storage silos and irrigation pipes | - Weather resistance<br>- Cost-effective solutions |
| Waste Management | - Composite bins for segregation<br>- Composting units made of polymer composites | - Durable and hygienic<br>- Easy to clean and maintain |

Integrating composite materials into Smart Village development provides a sustainable, cost-effective, and resilient alternative to conventional materials. Their adaptability across housing, infrastructure, energy, and sanitation makes them essential to the success of smart and sustainable rural transformation.

### 1.1. Composite composition

**1.1.1 Matrix Material**: The matrix material serves as the core or bulk of the composite, providing structural integrity and holding the reinforcement and filler materials together. It can be a polymer (such as epoxy, polyester, or thermoplastic), a metal (like aluminum or titanium), a ceramic, or even a hybrid of these materials. The matrix material is chosen based on factors like its compatibility with the reinforcement and filler materials, desired mechanical properties, chemical resistance, and cost-effectiveness. It also plays a crucial role in determining the composite's overall mechanical and thermal behaviour.[24]

**1.1.2. Reinforcement Material**: Reinforcement materials are added to the matrix to enhance specific properties of the composite. These materials are typically stronger and stiffer than the matrix material, and they help distribute loads and improve mechanical characteristics. Common reinforcement materials include:

Fibers: These are often used in the form of continuous strands or woven fabrics. Common fiber materials include glass, carbon (carbon fiber), aramid (Kevlar), and natural fibers like bamboo or flax. Each type of fiber offers unique properties, such as high tensile strength (carbon), impact resistance (aramid), or corrosion resistance (glass).

Particulate Materials: These are typically small, solid particles added to the matrix. Examples include silica, alumina, or even metal powders. Particulate fillers can improve properties like hardness, wear resistance, or thermal conductivity.[24]

**1.1.3. Filler Material**: Filler materials are fine particles or additives dispersed within the matrix. Unlike reinforcement materials, which primarily enhance mechanical properties, fillers serve various functions depending on the composite's intended application. Common filler materials include:

Nanoparticles: Extremely small particles, often at the nanoscale, like nano clays, nanotubes (such as carbon nanotubes), or nanoparticles (like titanium dioxide). These can improve mechanical strength, thermal conductivity, and electrical properties.

Microspheres: Hollow microspheres or micro balloons, often made of materials like glass or polymers, can reduce the density of the composite, making it lighter while retaining strength.

Functional Fillers: Fillers can also be used for specific purposes, such as flame retardants, UV stabilizers, or colorants, to enhance the composite's resistance to environmental factors or provide aesthetic qualities.

The combination of these three components—matrix, reinforcement, and filler materials—allows for the creation of composite materials with tailored properties. The choice of each component depends on the desired characteristics and intended applications of the composite. Composites are versatile materials widely used across industries due to their ability to achieve a balance of properties that may not be attainable with single materials.[24]

**1.2. Materials that were choose:**

**a) Coir** - Coir is the fibrous material found between the hard, internal shell and the outer coat of a coconut. It would be the reinforcement part of the composite. Coir fibers enhance the composite's mechanical properties, such as tensile strength and impact resistance. They provide natural reinforcement, making the composite sturdier and more resilient.

**b) Polyester Resin** - Polyester resin is the matrix material in the composite. The polyester resin serves as the primary structural component, binding the other materials together. It provides strength, durability, and stability to the composite. Additionally, it helps protect against environmental factors and corrosion.

**c) Magnesium Hydroxide** ($Mg(OH)_2$) - Magnesium Hydroxide is a fire-retardant filler material. $Mg(OH)_2$ serves as a fire-resistant agent, providing the composite with fire-retardant properties. It can suppress and slow down the spread of flames, making the composite safer in fire-prone environments.

## 2. Review of Literature

**R. Kurinjimalar et al**. studied about mechanical properties, coil fibre reinforced compounds, chemical treatments, morphological analysis, tensile strength, application in concrete, and the mechanical properties of an object are usually tested under a given load. The natural thread of mechanical properties is compound and structural defects in many affected the most common advanced compounds are polymer matrix compounds. These compounds can be fibre-reinforced polymer thermoplastic or thermosetting. Chemical modification can make fibre Cell walls are highly dimensionally stable, which can reduce water absorption resistance or increase fungal decay, but not cause decay.[1]

**D. Vermal et al.** studied how agricultural wastes can be used to prepare fibre reinforced polymer composites for commercial use. Although glass and other synthetic fibre-reinforced plastics possess high specific strength, their fields of application are very limited because of their inherent higher cost of production. In this connection, an investigation has been carried out to make use of coir; a natural fibre abundantly available in India. This review discusses the use of coir fibre and its current status of research. Many references to the latest work on properties, processing and application have been cited in this review.[2]

**K.M Faridul Hasan et al.** presented a review which provides an overview of coir fibre and the associated composites along with their feasible fabrication methods and surface treatments in terms of their morphological, thermal, mechanical, and physical properties. Furthermore, this study facilitates the industrial production of coir fibre-reinforced bio composites through the efficient utilization of coir husk-generated fibres. [4]

**I. Mawardi et al.** researched to obtain the impact characteristics of epoxy composite hybrids through multi reinforcement. The hybrid composites fabricated by three variations. Short coconut fibre is produced by fibrillation process. Hand layup process was used to prepare the specimens. In each variation, the first layer consists of coir+ Epoxy + Alumina. Impact test is performed to determine the mechanical properties. The results showed that the variation 1 had the highest impact strength of 58.02 kJ/m2 while the lowest impact strength in the variation II, which is 41.13 kJ/m2. The fracture occurred in the form of brittle fracture.[5]

**Akash et al.** studied experimental results of a fire-retardant behavior and moisture absorption behavior of different weight percentage (10, 20, 30, 40 and 50 wt. %) of sisal/coir fiber reinforced epoxy resin hybrid composites. Traditional cold pressing method was used to fabricate hybrid composites. Flammability behavior of the hybrid composite was studied by using vertical and horizontal burning rates as per standard UL-94. Addition of the cellulosic fiber increases the flammability since natural fiber supports fire. It proves as a bad flame retardant due to the generation of a surface layer during pyrolysis of the cellulosic fiber which exhibits poor fire-retardant nature. This layer acts as supporter of fire, which spreads the heat from being transferred to the un-pyrolyzed material.[3]

**Kalmanje Mugdha Bhat et al.** researched on the effect of fiber content on the properties of natural fiber reinforced composites, is particular significance. An important factor that significantly influences the properties and interfacial characteristics of the composites is the processing parameters used. Biocomposites offers a significant market in automotive and decking market but application in other sectors has been limited. Green composites are promising because they are renewable, biodegradable and sustainable for non-renewable composites.[6]

**C. R. Rejeesh et al**. aimed this study towards improved fire resistance in coir fibreboards using fire-retardant (FR) boron solutions. Different blends of borax and boric acid were applied to the samples. The treated boards showed enhanced resistance to fire, slower burning, and better protection against flame spread. Through regression analysis, researchers accurately linked the weight percentage of FR boron in the solution to flame resistance. They concluded that a 35% boron solution offered the highest fire resistance for these fiberboard samples.[7]

**Chizoba Obele et al.** researched on formulating Coir fiber/epoxy resin composites at different filler loadings for potential helmet shell fabrication, producing promising results. Through flexure, impact, and tensile testing, it was found that the optimal tensile strength (23.68 N/mm2) and Charpy notch impact strength (26.43 KJ/m2) occurred at a 30 wt.% filler loading, although beyond this point, strength decreased. These values closely matched those of Polycarbonate (PC) and Acrylonitrile butadiene styrene (ABS), commonly used for helmet shells. The tensile modulus increased with filler loading and, while slightly lower than ABS, these composites (fabricated via hand lay-up technique) were employed in industrial helmet production to reduce costs.[8]

**Rahul Shrivastava et al.** studied that though natural fiber possesses good properties yet their affinity towards water and improper matrix interface bonding are major concern. Due to this challenge strength of composite is considerably affected. Uses of synthetic fibers do not impose any challenge as the natural fibers, but they are non-biodegradable and cost more than natural fiber. In present work properties of both synthetic and natural fibers are utilized in a way to improve the mechanical properties. For this purpose, naturally occurring coir fiber and synthetic glass fiber mats are used as reinforcement while thermosetting polymeric resin Epoxy is used as matrix material. To decrease moisture absorption behavior of coir fiber, it is chemically treated with Sodium hydroxide. This chemical treatment reduces the affinity of fiber towards material and increases surface roughness thus results in better matrix reinforcement interface bonding. Short coir fiber /glass fiber mat hybrid composite is fabricated by hand-layup method. The study confirms that the mechanical properties of the composites are varies with volume fraction and fiber length of the fibers.[9]

**Suad H. Aleabi** researched on a composite material consisting of unsaturated polyester (UPE)resin reinforced by mullite particles with different weight ratios (0, 20, 40, and 60 wt.%) was prepared. The samples were studied for the effect of adding mullite on the electrical and mechanical properties of the composite. The composite material was prepared by a hand lay-up molding method. The results showed that the electrical properties (the real and imaginary dielectric constants) increased after reinforcement with the addition of mullite content but reduced with increasing frequency, whereas electrical conductivity reduced with increasing frequency and mullite content. The mechanical properties (tensile strength and hardness) increased after reinforcement with an increasing mullite content.[10]

**Santosh Kumar et al**. focused on the study of fracture toughness behavior of these composites and further characterization of mechanical properties. The fabrication of the specimen was carried out using Injection moulding technique. Fracture toughness (Compact Tension) tests were done as per ASTM D-5045 standards. The Tensile, Impact, Flexural Strength, and Hardness tests were done to evaluate the mechanical characteristics. It is found that natural coconut coir fiber reinforced composites showed higher fracture toughness values and improved mechanical properties when compared to neat polypropylene.[11]

**Md Rayhan Hasnat et al.** articulated a comprehensive review of the research trend along with the most cited publications. Most cited articles were chosen to observe the developments. The data collected from the Scopus database in the second week of March 2023 were also categorized to present country-wise improvement, the subject areas involved, and the author's contribution to the topic. Some issues and challenges have also been highlighted from the analysis. By observing the research direction and highly cited articles, some of the further study scopes are also pointed out to develop fire-rated polymer composites for use as sustainable cladding materials for high-rise buildings.[12]

**C.R. Rejeesh et al.** published a paper which reviews the potential of coir composites and types of composite boards currently available. It also covers the different types of flame retardants (FRs) that can be used and their mechanisms for inhibiting fire, and discusses the various methods of fire-retardant treatment.[13]

**C. R. Rejeesh et al.** researched and published an article which investigates the effect of fire-retardant (FR) treatment on mechanical and physical properties of medium-density coir fibreboards when treated with a waterborne solution containing boron compounds using the method of hot and cold bath treatment. The results obtained were encouraging, and it was observed that the coir fibreboards after FR treatment retained much of their properties and in many cases, even improved marginally.[14]

**Mahadev Bar et al.** reviewed on different approaches of enhancing flame retardancy of polymeric composite material and their effect on different composite properties are analysed critically. Flame retardancy of polymeric composite material can be enhanced either by enhancing the fire performance of constituents of composite i.e. matrices and reinforcing agents or by providing a protective flame retardant (FR) coating around the composite material. Fire performance of reinforcing material is improved by treating with FR-chemicals while the fire performance of polymer matrices can be improved by incorporating micro and nano FR-fillers or by introducing FR-compound into polymer backbone [15]

## 3. Research Methodology

### 3.1 Alkaline Treatment

The hydrophilic nature of coconut coir acts as undesirable characteristics which makes it unsuitable for many industrial applications. Some of the ill effects of hydrophilic nature of coconut coir include the growth of pathogens and enlargement of coir by absorption of moisture from the surrounding air. The coconut coir was chemically treated in order to remove the lignin and pectin capable to degrading its properties under the influence of moisture. A solution containing 7% Sodium Hydroxide (NaOH) in water was added to coconut whiskers.[23]

The solution was allowed to react with the whiskers for 48 hours for sample 1 and 72 hours for sample 2, and then drained. The chemical reaction that takes place during the treatment of the coconut fibre is shown by the equation

Coconut fibre + NaOH → O + Na + Coconut threads

**Fig. 3.1 Alkaline treatment of coir**

**Fig. 3.2 Drying of treated coir**

The resulting coconut fibres with its hydrophilic nature removed were washed in distilled water to remove the traces of NaOH. The whiskers were then dried under sunlight for two days to remove excess moisture on their surface.

### 3.2 Tensile test coir fibre

#### 3.2.1 Tensile test of treated coir fibre

This test was conducted in a Micro UTM (Universal Testing Machine). Single strands of coir fibre (both treated and untreated) were taken and tested for their tensile strengths.


**Fig. 3.3 Micro UTM**

**Fig. 3.4 Treated fibre**

**Procedure-**

1. The load cell was assembled onto the Micro UTM.
2. A strand of untreated coir was fitted between the jaws connected to the load cell. As shown in fig. 8.2.
3. The mains supply was switched on and the PC as well.
4. All the required data were inputted into the software.
5. Test was run until the sample tore.

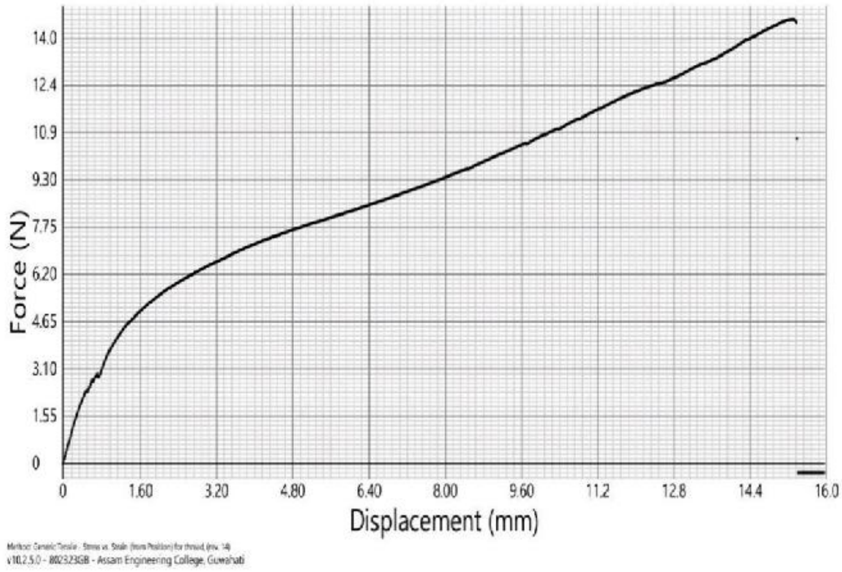



**Fig. 3.5 Force vs displacement curve for treated coir fibre.**

**Result:**

**Table 3.1 Results of Tensile test (treated coir fibre)**

| Parameter | Result |
|---|---|
| Ultimate force (N) | 14.6 |
| Break distance (mm) | 15.4 |
| Total elongation (%) | 39.5 |

### 3.2.2 Tensile test of untreated coir fibre

**Fig. 3.6 Untreated fibre**

**Procedure-**

1. The load cell was assembled onto the Micro UTM.
2. A strand of untreated coir was fitted between the jaws connected to the load cell. As shown in fig. 8.4.
3. The mains supply was switched on and the PC as well.
4. All the required data were inputted into the software.

5. Test was run until the sample tore.

**Result –**

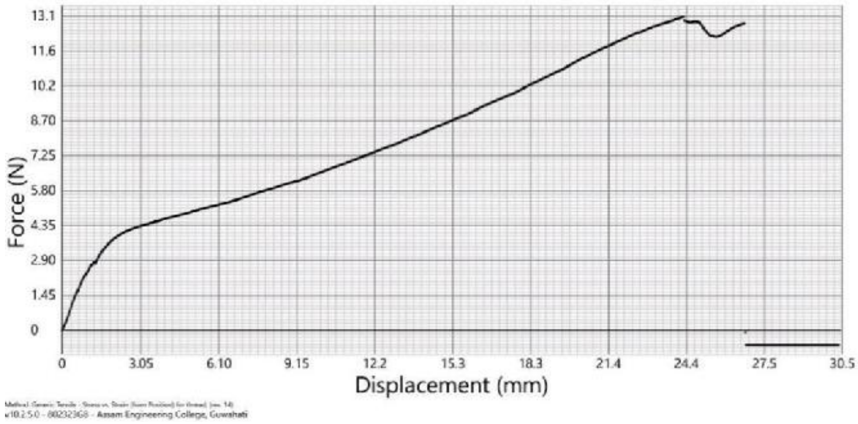



**Fig. 3.7 Force vs displacement curve for untreated coir**

**Table 3.2 Results of Tensile test (untreated coir fibre)**

| Parameter | Result |
|---|---|
| Ultimate force (N) | 13 |
| Break distance (mm) | 30.4 |
| Total elongation (%) | 40.5 |

**Conclusion –**

It has been seen that there was an increase in ultimate force for the treated coir fibre, hence we can conclude that NaOH treated coir fibres exhibit higher tensile strength.

### 3.3 Hand Layup Method

The specimens were manufactured to evaluate the variation in its mechanical properties and compare the same with the existing material for desired appliance. The composite materials were manufactured using hand layup technique because of its capability of making large sized composite material at relatively lower cost. Shows the composition of the composite material used in the research.[5]

A flat plastic mold plate of size 250×140 mm was used for manufacturing of the composite materials. Heavy duty silicon wax spray was used for separating layer to avoid sticking of the composite material to the mold. The binder cum matrix composing of resin and catalyst was taken in the ratio of 96.25:1. Hence 8 ml of catalyst was added to 1 kg (density = 1.3 kg/cm$^3$) of polyester resin. 10.59% by weight of Magnesium hydroxide was mixed with the mixer. 4.57 % by weight of chemically treated coconut fibres were taken. [23]

**Fig. 3.8 Coir**

**Fig: 3.9 Plastic Mould**

The resulting mixture was poured evenly over plastic mold plate. The alkaline treated coconut fibre was placed over the binder mixture. The fibre layer was topped with a second layer of the binder mixture. This arrangement gave 2/1 layup for the produced composite laminate. The polypropylene sheet was used as cover over the top layer of binder and whisker mixture. A flat wooden plate was place over the top polypropylene sheet. Then weights were kept over the surface of the wooden plate. The weights gave the necessary force to press the components of the composite material and spread it evenly along the mat.

For the second sample we altered the coir percentage to 6.88% and rest of the components were kept same.

The excess materials which came out along the sides of the mold were scrubbed out. The layup was left untouched for duration of 24 hours so as to allow sufficient setting time and curing. Then the cured composite material was removed from the mold. The average thickness of the composite material was measured as 8 mm. Figure 3.10 shows the composite material manufactured using hand layup technique. The specimen is further cut into specific dimensions to facilitate the numerous tests to be conducted.

**Fig. 3.10 Composite material after demolding.**

**Fig. 3.11 Composite material cut into specimens. (sample 1)**

**Fig. 3.12 Sample 2**

### 3.4 Tensile Test

Tensile testing is a destructive test process that provides information about the tensile strength, yield strength, and ductility of the material. Tensile testing of composites is generally in the form of basic tension or flat-sandwich tension testing in accordance with standards such as ISO 527-4, ISO 527-5, ASTM D 3039, and ASTM C 297. [11]

**Preparation of specimen:** Before starting the test for tensile strength, the specimen needs to be prepared in advance. The specimen can be cut using a hacksaw. Alternatively, we used a chow saw instead.

**Fig. 3.13 Specimen used in tensile test**

The 1st sample is of width 35mm, thickness 17.5mm and gauge length 50mm. The 2nd sample is of width 25mm, thickness 20mm and gauge length 50mm. Each end of the specimen is gripped in a tensile testing machine, which applies tension until the specimen breaks. The cross-section is rectangular in shape.

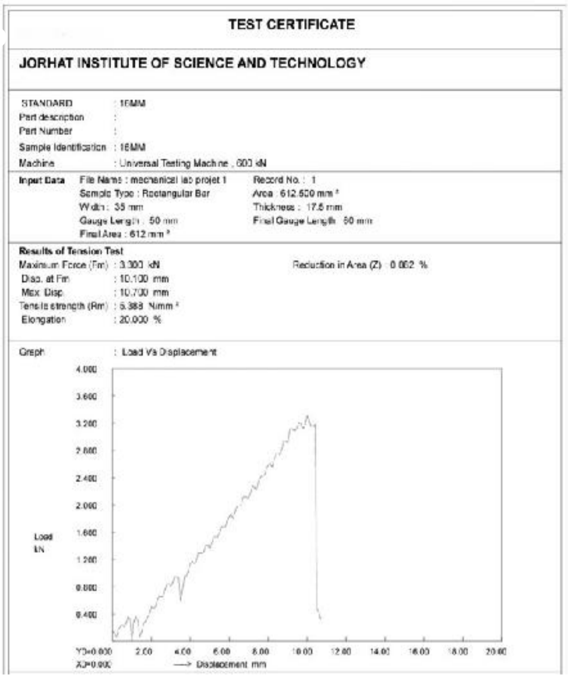
The tester needs to change the settings on the software before starting the test. This is because each test requires the correct settings according to the test standards. This setting also depends on the type of test to be performed and also depends on the type of material.

After installing the specimen, attach the extensometer to its length. While it undergoes testing, the extensometer will be monitoring and measuring any changes in the material. After the extensometer is placed, double-check the other equipment to make sure they are in their correct positions.

To begin the tensile stress test, slowly separate the tensile clamps at a constant speed. The tensile testing took five minutes or less for the material to fracture.

.The data gathering software will present the material's test parameters, as well as the changes in the gage length. It will monitor the force placed upon the specimen and display the stress-strain curve. The stress-strain curve is helpful in analysing the specimen's behaviour throughout the test.[17]

## Results


TEST CERTIFICATE

JORHAT INSTITUTE OF SCIENCE AND TECHNOLOGY

STANDARD : 16MM
Part description :
Part Number :
Sample Identification : 16MM
Machine : Universal Testing Machine , 600 kN

Input Data File Name : mechanical lab projet 1 Record No. : 1
Sample Type : Rectangular Bar Area : 612.500 mm²
Width : 35 mm Thickness : 17.5 mm
Gauge Length : 50 mm Final Gauge Length : 50 mm
Final Area : 612 mm²

Results of Tension Test
Maximum Force (Fm) : 3.300 kN Reduction in Area (Z) : 0.082 %
Disp. at Fm : 10.100 mm
Max Disp. : 10.700 mm
Tensile strength (Rm) : 5.388 N/mm²
Elongation : 20.000 %

Graph : Load Vs Displacement



**Fig. 3.14 Test certificate of Tensile test (specimen 1)**

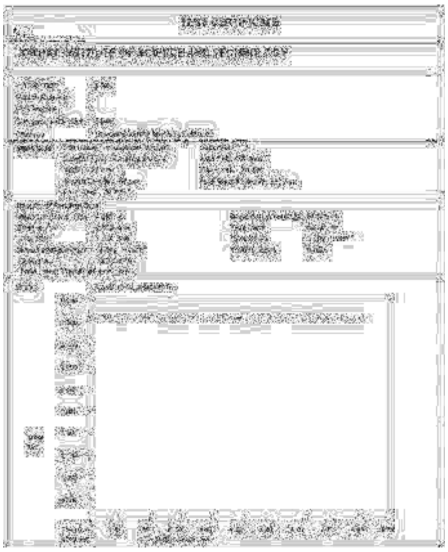


**Fig. 3.15 Test certificate of Tensile test (specimen 2)**

**Table 3.3 Results of Tensile Test**

| Specimen no. | Tensile strength (N/mm$^2$) | Maximum force (KN) |
|---|---|---|
| 1 | 5.388 | 3.3 |
| 2 | 14.940 | 7.470 |

### 3.5 Compression Test

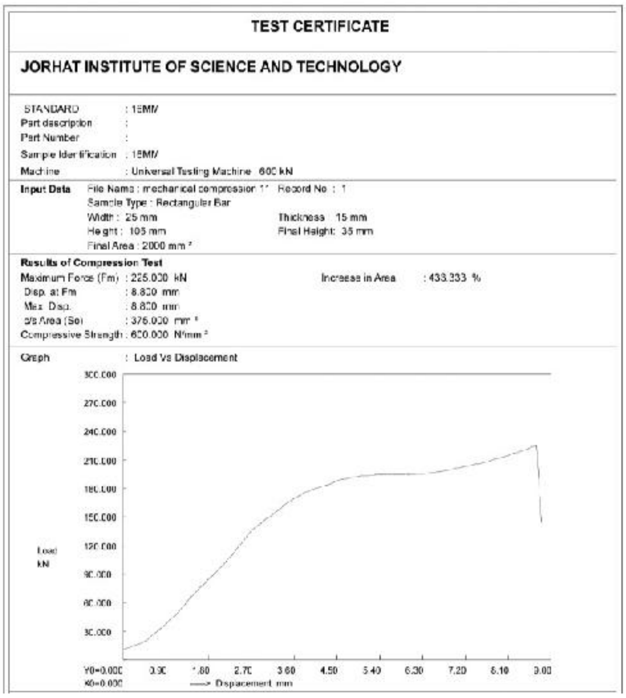
In a compression test, a sample of the material is placed between two plates or jaws of a testing machine. A compressive force is applied to the sample until it reaches a specific deformation or until it fractures. The machine, a deflectometer or an extensometer, can be used to measure the deflection or strain of the sample.[18]

**Preparation of specimens:** Most international standards prescribe a specific geometry for material test samples. These defined shapes and sizes generate standardized and relevant results even out of different testing rigs. Therefore, before testing, it needs to be formed into the proper shape. The specimen prepared is of width: 25mm, height :105mm and thickness:15mm. [19]

**Fig. 3.16 Specimen for compression test**

**Fig. 3.17 Specimen set onto UTM**

**Results:**



TEST CERTIFICATE

JORHAT INSTITUTE OF SCIENCE AND TECHNOLOGY

STANDARD : 15MM
Part description :
Part Number :
Sample Identification : 15MM
Machine : Universal Testing Machine 600 kN

**Input Data** File Name : mechanical compression 11 Record No : 1
Sample Type : Rectangular Bar
Width : 25 mm Thickness 15 mm
Height : 105 mm Final Height: 35 mm
Final Area : 2000 mm ²

**Results of Compression Test**
Maximum Force (Fm) : 225.000 kN Increase in Area : 433.333 %
Disp. at Fm : 8.800 mm
Max. Disp. : 8.800 mm
c/s Area (So) : 375.000 mm ²
Compressive Strength : 600.000 N/mm ²

Graph : Load Vs Displacement

**Fig. 3.18 Test certificate for compression test (specimen 1)**

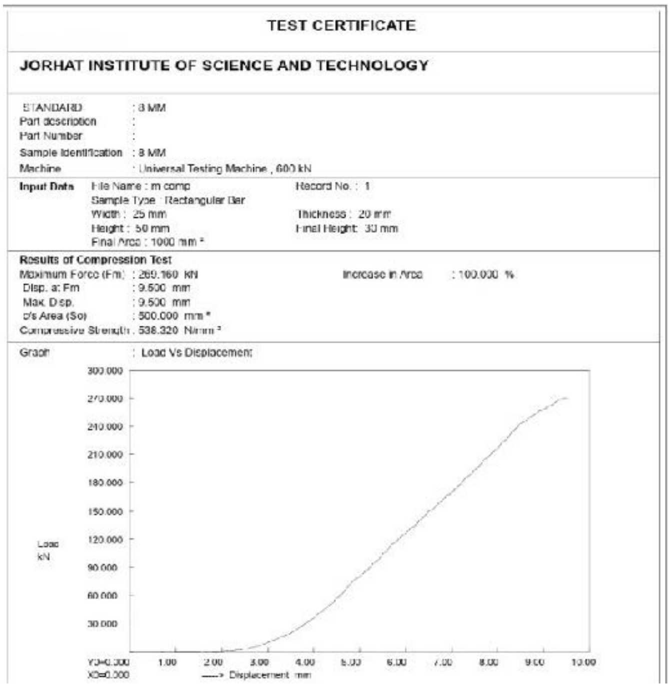



**Fig. 3.19 Test certificate for compression test (specimen 2)**

**Table 3.4. Results of Compression Test**

| Specimen no. | Compressive strength ($N/mm^2$) | Maximum force (KN) |
|---|---|---|
| 1 | 600 | 225 |
| 2 | 538.32 | 269 |

## 3.6 Charpy Impact Test

The Charpy impact test, sometimes called a V-notch test, is a comparative-style test used to define a material's impact strength by determining how much energy is required to fracture a pre-prepared and standardized sample with a V-notch machined into it. A pendulum is released to strike the specimen. The height of the pendulum before and after passing through the sample is used to calculate the energy absorbed during the fracture process.[20]

**Prepare Sample -** The samples must be prepared with dimensions according to the relevant standard. There are multiple standards used. The sample size used is 70×20×16 mm. The testing standard will also dictate how many samples must be tested.

**Result –** **Table 3.5 Results of Charpy Impact Test**

| Specimen no. | Impact energy (J) | Impact strength (J/mm) |
|---|---|---|
| 1 | 26.6 | 1.6625 |
| 2 | 48.3 | 2.415 |

**Fig. 3.20 Burning of specimen**

**Fig. 3.21 Specimen after completion of test**

**Results:**

**Table 3.6 Results of Horizontal Flammability Test**

| Specimen no. | Ignition time (s) | Burning time (s) |
|---|---|---|
| 1 | 22.24 | 406 |
| 2 | 21.63 | 452 |

### 3.7.2 Standard Test Method for Measuring the Comparative Burning Characteristics of composite material in a Vertical Position (ASTM D3801-20a):

As compared to the previous test (ASTM D635-22), this test method was also developed for polymeric materials used for parts in devices and appliances. The results are intended to serve as a preliminary indication of their acceptability with respect to flammability for a particular application.

**Procedure:**

1. The specimen is first cut to specific dimensions of 250×20×28 mm.
2. The specimen is then mounted on a burette stand on a vertical position.
3. It is then ignited at one end and the ignition time is recorded.
4. The ignition source is then removed after the specimen starts igniting.
5. The burning behavior is observed and burning time is recorded.
6. After the burning halts the end point is noted.

**Results**:

**Table 3.7 Results of Vertical Flammability Test**

| Specimen no. | Ignition time (s) | Burning time (s) |
|---|---|---|
| 1 | 37.32 | 88 |
| 2 | 35.12 | 111 |

## 4. Comparative Study

We conducted a comparative study between the coir-based composite we fabricated and commonly used woods in furniture. We compared their mechanical properties and prices with a sole objective in mind, i.e. to determine whether this composite can be used as a replacement of wood to make tables, doors, etc.

**Table 4.1 Component wise price distribution (coir composite)**

| Material | Price per kilogram (rupees) | Price of material required in one sample of 25×15×3 (cm) (rupees) | Price per cubic feet (rupees) |
|---|---|---|---|
| Polyester resin | 90 | 90 (for 1 kilogram) | 2265 |
| Magnesium hydroxide | 80 | 10 (for 125 gram) | 251 |
| Coir | 0 | 0 | 0 |
| Total price | 170 | 100 | 2516 |

**Table 4.2 Market Price of different woods**

| Type of wood | Price per cubic feet (rupees) | Average price per cubic feet (rupees) |
|---|---|---|
| Teak | 600-1000 | 800 |
| Pinewood | 400-750 | 575 |
| Rose Wood | 1500-6000 | 3750 |
| Satin Wood | 1250-1500 | 1375 |
| Sal Wood | 1250-1500 | 1375 |
| Shisham Wood | 1500-2500 | 2000 |
| Marandi Wood | 900-1400 | 1150 |
| Mahogany | 850-2500 | 1675 |
| Mulberry | 1500-2500 | 2000 |
| Deodar | 550-2500 | 1525 |
| Jackwood | 1200-2900 | 2050 |

**Table 4.1 Mechanical Properties (Wood vs Composite)**

| Mechanical property | Wood | Coir composite |
|---|---|---|
| Tensile strength (MPa) | 70-140 | 14.94 |
| Compressive strength (MPa) | 30-60 | 600 |
| Charpy impact energy (J) | 7.3 | 48.3 |


**Fig. 4.1 Price comparison (Composite vs Wood)**

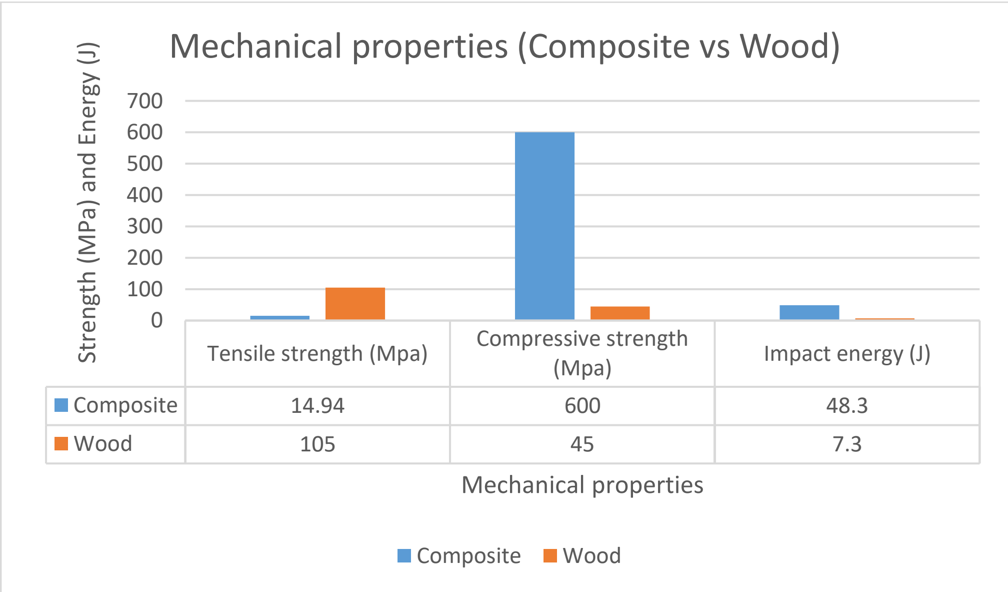



**Fig 4.2 Mechanical properties comparison (Composite vs Wood)**

## 6. Conclusion and Future Scope

The coconut fibres are successfully reinforced with the polyester resin by simple hand lay-up technique. The aim is to seek out the tensile, compression, impact strength and flammability test of coconut fibre reinforced composites. The new composite samples produced with coconut fibres as reinforcements gives tensile strength of 5.388 N/mm$^2$ and 14.940 N/mm$^2$, compressive strength of 600 N/mm$^2$ and 538.32 N/mm$^2$, impact strength turns out to be 1.6625 J/mm$^2$ and 2.415 J/mm$^2$. The form of fracture that occurs on composite is a brittle fracture. The flammability test results prove to be satisfactory as per the need of the project.

The composite produced can be used as a replacement for wood as raw material. The final products of the composite can be doors, almirah, table etc. This composite accompanies an additional feature of being fire resistant. This feature can lead to an advantageous situation while facing hazardous conditions like house fire.

In terms of sheer performance, the coir-based composite material appears to be a strong contender for replacing wood in furniture applications. Its superior mechanical properties and fire resistance provide clear advantages. However, the current cost disadvantage is a significant hurdle. If production costs can be lowered through economies of scale, and if the market can be educated about the benefits of this new material, it has the potential to gain a substantial foothold in the furniture industry. The key to success will be balancing performance with cost-effectiveness and ensuring that the material meets both functional and aesthetic expectations of consumers. Additionally, emphasizing the sustainability of the composite could further enhance its appeal in a market increasingly concerned with environmental impact.

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# A REVIEW ON USES OF SISAL FIBERS FOR SOIL IMPROVEMENT

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***Abstract:*** *As one of the high-strength natural fibers, Sisal Fiber (SF) could help in soil conservation and solve the natural field geotechnical problems that rural villages face. The limited access to borrowed geomaterials constricts the ability to develop rural infrastructure. The present study aims to illustrate the geotechnical improvements on the incorporation of sisal fiber on different soil types. The laboratory investigations on the strength and durability of the SF have been reviewed for its performance efficiency as a standalone and as a secondary additive in soil reinforcements. Despite possessing superior mechanical characteristics, there has been a lack of awareness and adoption about its potential uses in rural areas for slope stability, erosion control and resilient infrastructure. The review also highlights the limitations, future scope and sustainability considerations of the SF-treated soils.*

## 1 Introduction

Soil is a porous medium possessing fluctuating geotechnical features, and the infirm soils require treatment when used as an engineering geomaterial. Most commercially available chemical additives and manufactured reinforcing materials for soil improvement are fabricated from synthetic polymers that are produced utilising petroleum, an unsustainable fossil resource, as feedstock. They lack biodegradability. Consequently, they provide a significant disposal challenge once reaching the end of their lifespan. The environmental degradations, including climate change, jeopardise the natural equilibrium of the soil and groundwater ecosystem (Liu et al. 2021). The notion of sustainable development is primarily founded on balancing social and economic necessities with the planet's available resources. Environmentally sustainable construction materials, natural resources, reduce pollutant emissions and enhance energy recovery. Earth reinforcement approach has been employed to enhance specific desirable characteristics of soil such as shear strength, permeability, compaction and bearing capability. The reinforcement of soils has achieved broad popularity in applications of geotechnical engineering due to its advantages of economy, accessibility, straightforward handling, resource management and being ecologically sustainable. Consequently, the soil reinforcement technique is regarded as an efficient ground enhancement technique due to its cost-effectiveness and ease of adoption (Gowthaman et al. 2018). Architects, engineers, and constructors have been advancing the use of natural materials for construction as a viable method for generating more sustainability due to increasing concerns regarding climate transformation, resource exhaustion, and ecological deterioration in recent years. The primary component influencing this is its small ecological imprint, increasing focus on natural materials in construction. By utilising sustainable materials, construction projects can reduce their carbon footprint.

Historically, many natural fibers have been utilised to enhance the soil properties in traditional earthen buildings. Conventional inorganic fibers, like glass and carbon, are cost-effective and lightweight, exhibit comparatively elevated tensile strengths and flexural moduli of elasticity, and are not biodegradable. A multitude of natural fibers, such as bamboo, palm, areca, coir, and jute, have been utilised over the years to enhance the mechanical properties of various soil types. Recently, plant-derived natural fibers have been extensively utilised in the fabrication of thermoplastic composites due to their advantages over alternatives. The high-strength properties of SF are intricately linked to their chemical composition. Sisal is a robust fiber derived from the leaves of the sisal plant, primarily composed of cellulose, Hemicellulose, and lignin. SF is often derived from the foliage of the sisal plant Agave sisalana, which varies in thickness, ranging from 6 to 10 cm and length from 50 to 250 cm, processed with machinery (Zafar et al. 2023). SF possesses a low density of approximately 15 $kN/m^3$, yet exhibits a tensile strength of 550 $MN/m^2$ with Young's modulus of 24 GPa (Oksman et al. 2002). Examining the application of SF in geotechnical engineering reveals both its potential and the challenges inherent to this natural material. SF is recognised for its durability, strength, and resistance to abrasion under harsh conditions (Mayakannan et al. 2023). The mechanical advantages they provide in soil applications are enhanced by the sustainable characteristics of the fibers and the prudent management of the resources from which they originate. SF is an appealing candidate for utilisation as a reinforcing material due to its textural, tensile, and frictional properties. SF, as a reinforcing material, has immense benefits to the environment due to its sustainable characteristics. The primary aim of this review is to investigate the efficacy of the SF in soil reinforcement applications to enhance soil sustainability in land use.

## 2 Discussion on the strength and durability of the SF-treated soils

### *2.1 Strengthening behaviour of the SF-treated soils*

Deng et al. (2025) reported a 43% increase in Unconfined Compressive Strength (UCS) of the SF-treated silty clay due to the enhanced friction and traversing in the soil. The behaviour of the SF-treated clay after the UCS peak load indicated a reduction in strength loss with extended periods of time, and the failure pattern revealed only minor cracks accompanied by bulging of the clay specimen. The SF-treated clay did not fail immediately as observed in the untreated soil, indicating greater energy absorption and toughness. Excess dosage beyond the 0.9% resulted in imbrication of the SF, causing a 9% drop in the strength. A 97% increase in UCS is attributed to the interlocking of the SF into the soil, while the excess SF separated the soil-SF mix; thus, preventive thorough mixing (Ramani Sujatha et al. 2017). The biochemical characteristics of fibers are crucial for the functionality of lignocellulosic fibers as soil reinforcement materials. SF primarily consists of cellulose, hemicellulose, pectin, and lignin, which collectively establish a resilient framework (Fan et al. 2021). Comparison of xanthan gum (XG)-treated silty clay soil with that of SF soil revealed that the XG-treated clay produced higher UCS, whereas the addition of SF reduced the brittleness and increased the resistance against repeated loads by 28% due to its tensile and crack-arresting properties (Aneke and Kalumba 2024). Lignin acts as a protective barrier that prevents the interior structure of the fiber from deterioration. The variation in strengthening effects of the SF-treated soils is associated with their rough texture, providing frictional interlocking with the soils, and filling up the soil voids by the SF functioning as a tensile reinforcement (Gehlen et al. 2025). Triaxial test revealed the maximum increase in cohesion by 266% and a negligible rise in friction angle, while the SF length exceeding 2 cm and 0.75% produced lower frictional interplay with the clayey soil (Prabakar and Sridhar 2002). The inherent ductility of the soils, coupled with the advantageous properties of SF, demonstrates positive effects on the enhancement of waste management (Jr Savastano et al., 2006). This is particularly applicable when utilized with engineered cementitious materials or soils treated with enzyme-induced calcite precipitation (EICP). The SF filaments function to interlock particles within a unitary coherent matrix and enhance the strength. In addition, SF has synergistic benefits when used as a secondary additive for ground improvement. Bu et al. (2024) demonstrated the combined efficacy of SF and polyacrylamide (PAM) in resistance to cracks and retention of moisture on the clay soil, respectively. However, the individual addition of SF and PAM separately did not improve both outcomes, indicating that the dual additive is functionally efficient in mitigating the dangers associated with slope instabilities. The arbitrary incorporation of fibers promotes preserving the isotropic strength and averting the potential formation of failure planes along the parallel orientation of the reinforcement [2,3]. Sani et al. (2020) reported a 592% rise in the UCS of a lateritic soil (LS) upon the combined addition of rice husk ash (RA) and SF. The increase is attributed to the bonding of the RA with water, leading to adhesive compounds and SF bridging the soil particles together. When flyash with SF was added to a medium compressible clay, a 33% reduction in carbon emission was observed. The cumulative deformation of the soil sample that had been reinforced with SF was significantly lower than that of the sample that had not been treated. The UCS was also improved by 34% due to the bonding of the flyash with the clay and enhanced interfacial strength due to the SF addition. Nonetheless, flyash addition in soils exhibits elevated stiffness and brittleness, along with adverse effects affecting the natural environment. The reduction in emissions was due to the enhanced California Bearing Ratio (CBR) by 37% which led to the decreased pavement sections (Kumar and Panwar 2019). Jena et al. (2025) compared the CBR of untreated, alkalescent SF and epoxy alkalescent SF geotextiles on a superimposed soil and the resistance to penetration increased by 365%, 292% and 331% respectively. The addition of SF beyond the optimum dosages leads to improper mixing and agglomeration, and thus, a drop in the compactness and poor mixing is observed (Xia et al. 2025). Paul et al. (2022) combined waste plastic strips and SF to increase the CBR of a highly compressible clay by 25% and the inclusion of SF improves the toughness of the treated clay. Cellulose, being the principal structural element, imparts considerable strength to the SF-treated clay soil (Wang et al. 2019). The strength improvement is not only because of the properties of the cellulose but is also attributed to its crystalline structure (Arun et al. 2024). Lu et al. (2024) demonstrated the combined effectiveness of SF with geopolymers on the improvement of a silty clay soil and noted that a 28% reduction in $CO_2$ emission was observed in addition to mitigating the swell-shrink variations of the soil.

### *2.2 Strengthening behaviour of the SF-treated soils*

Bu et al. (2023) observed an 82% reduction in crack width and an 81% reduction in crack ratio after the incorporation of 0.6% of SF into a clay soil after a threefold wetting and drying cycles (WDC) of the soil sample. The SF hinders the crack growth by engendering an additional frictional force with the clay particles, and the number of cracks on the surface of the clay is higher compared to the inner regions. This is attributed to the influence of water movement by the SF due to the dispersed orientation of SF, which increases the soil disparity and precludes the secondary and subsequent cracks on the clay, the results being more pronounced with increasing fiber dosages up to 0.6%. After 12 WDC for the durability assessment, a mass loss under 5% was noted upon the addition of SF and bottom ash for a compressed soil block (Thennarasan Latha and Murugesan 2024). With both dry and wet optimum water contents, the volumetric shrinkage of the SF-treated clay has been significantly reduced, emphasizing its durability (Yohanna et al. 2022). A comprehensive understanding of the SF-treated soils' characteristic curves could assist in the estimation of the water holding capacity and the hydro-mechanical characteristics of the soils. In addition, the degradation of the SF was analyzed for 12 successive weeks after its embedment into the soil and 73% tensile strength reduction was noted. After a series of 12 freeze-thaw cycles (FTC), the SF-treated silty clay exhibited a 59% reduction in deformation compared to the unreinforced soil (Deng et al. 2025). The multi-cycle FTC durability tests of an SF-geopolymer combined addition revealed the enhanced stability by 68% (Lu et al. 2024). The addition of SF contributed to mechanical reinforcements by forming a stable mesh-like structure within the soil. After 40 cycles of FTC, the UCS of the cement-treated sand with the addition of SF dropped a scant 16% (Xia et al. 2025). The incorporation of SF on riverbank slopes mitigates soil erosion owing to its moisture absorption characteristics (Ramkrishnan et al. 2018). The orientation of the SF, in addition to dosages and length, may influence the durability, and the vulnerability to deterioration in natural surroundings requires assessment. Tanko et al. (2018) analyzed the strength of the wax-cured SF-treated clay specimens for 7 days, followed by removal of the wax at both faces and subsequent submergence for a period of 7 days, compared to that of 14-day-cured specimens. The results revealed that the SF inhibited the strength loss with increasing dosages up to 1%. The utilisation of the SF also possesses intrinsic limitations, including biodegradability. Chemical polymer coating constitutes an efficacious remedy for circumventing the issue of biodegradability in natural fibers. Altering detrimental properties of fiber materials through chemical treatments might enhance SF-soil interactions and extend the SF's longevity. An increase in surface friction and increased mechanical interlocking performance is achievable by subjecting the SF to multiple treatments (Yahya et al. 2023). The alkaline treatment is one of the factors that can either positively or negatively affect the mechanical characteristics of fibers. Due to the hydrophilic nature of natural fibers, which causes them to absorb water, a consistent long-term performance may be challenging. In most cases, lignin, hemicellulose, and other impurities in fibers are eliminated with the application of an alkaline treatment. Additionally, the alkaline treatment of the natural fibers generates a variety of mechanical locking sites, which enhance the interfacial bonding.

## 3 Limitations and future directions of SF in ground improvement

Currently, natural fibers are extensively utilised in various technical applications industries such as the automobile, food, and agriculture. To effectively utilise SF in future endeavours, existing limitations are to be addressed. Research has affirmed the beneficial impacts of SF on the strength of the soils, yet there is a lack of significant data about the field performance of SF in the soil. Even though the precursor tests to a successful field implementation have been performed by simulating the field soil conditions under cyclic and dynamic loading, as well as testing of the soil-brick masonry wall component, the field implementation and pilot studies have not been conducted for the SF-stabilized soils. The inclusion of SF to the soil-brick masonry increased the wall panel strength by 150% and 220% under compressive and shear loading, respectively (Kafodya 2012). From a geotechnical perspective, the SF-stabilized soil's behaviour under cyclic loading resulted in an increase in shear modulus and damping ratio, up to 35% and 90% respectively. A 30% reduction in permanent strain and 23% increase in the energy absorption were observed compared for the SF-stabilized soil to the unreinforced soil. Under cyclic loading conditions, Aneke and Kalumba (2024) emphasized the SF's ability to hold the soil matrix together in spite of the microcrack formation in xanthan gum-stabilized soil. The enhanced ductility due to SF inclusion established a clear advantage over brittle stabilization materials and is particularly suited in low-volume roads and high-fatigue areas. Sarsby et al. (2006) inferred that under realistic field conditions of cyclic wetting and drying, SF exhibited a gradual strength loss from 135 kN/m to 17 kN/m over five years, directly satisfying the global factor of safety under rotational failure of a 3 m high embankment under non-aggressive water conditions. Future research is essential to conduct experiments with a broader category of soils under diverse field loading and environmental exposure conditions. Standardization of the SF's length, thickness, orientation and dosages for different soil types could lead to systematic evaluation of the engineering properties. The rate of degradation of the SF in soils and the corresponding mechanical characteristics are to be assessed in varying field conditions. The increase in durability of the SF by the introduction of chemical coatings is to be assessed for repeated durability cycles to ascertain the environmental toxicity (Behera et al. 2022). A detailed assessment of multiple treatments for the SF-treated soils with environmentally friendly techniques should be conducted to counterbalance the durability with the toxicity issues. SF's efficacy in real-world applications needs additional investigation, as well as the impact of biological mechanisms and extreme conditions should be thoroughly considered. SF possesses attributes that render it highly durable, low sustenance, and alongside being biodegradable. The local abundance and cost-effectiveness of fiber production, which demands minimal energy, render it highly beneficial for the population. The differences in the quality and engineering properties of the SF could also challenge its large-scale testing and adoption. Adoption of SF with standardized processing, increased durability, fabrication of bio-composites, and hybrid composites can influence its widespread adoption. The incorporation of SF into the soil renders the composite biodegradable, sustainable, environmentally friendly, and economically viable, while also exhibiting superior physical and mechanical properties. When it comes to performance, a soil-fiber blend does not depend on based solely on the characteristics of the elements among themselves, but in addition, in regard to the compatibility of the fibers with the soil. The interaction between the matrix and the reinforcement is what constitutes the contact area of the components in the mixture, which is the most important factor, for it is the process by which mechanical tensions are transferred from the matrix to a reinforcement that was provided (Oliveira Júnior et al. 2019). As a result, the connection the relationship between fibers and soil is essential for the improvement of the features of the composite material. The clay soil matrices exhibit a satisfactory level of attachment to fiber surfaces due to the arrangement, size, and distribution of the load between the surfaces the minerals that are found in clay.

## 4 Sustainability considerations

Sustainable infrastructure is essential for adjusting to climate change and advancing sustainable development, as it enhances resilience and efficiency in construction and land utilization. The utilisation of native soil without the need for borrowing a high-strength soil from the nearby vicinity for geotechnical purposes leads to resource conservation and economic advantages, especially in poor nations where material expenses coincide with labour costs (Basu and Lee 2022). Despite considerable efforts to enhance the stability of soil mass effectively, most endeavours lack environmental considerations in their performance. SF, in comparison to synthetic fibers, possess several advantages, including: cost-effective, with favourable mechanical characteristics, utilising very simple technologies, necessitating reduced energy for manufacturing and originating from renewable sources. The natural wastes yielded from the cultivation and processing of the SF can be redeployed for renewable energy, livestock fodder. The utilisation of locally sourced natural SF for geotechnical infrastructure has three primary benefits: enhancement of rural household income, elevation of socio-economic status within countries, and mitigation of climate change. The utilization of SF in soil reinforcement advances the agricultural sector through agribusiness, thus the downstream effect may enhance the income basis of rural households (Cantalino et al. 2015). Being a renewable material, the adoption of SF in geotechnical engineering directly translates to utilization of local resources and resistance to environmental conditions. The improvement in strength of the geomaterial leads to enhancement of soil's stability against erosion and in unpaved road improvement. The SF can also be used in combination with vegetative seeding until the establishment of vegetation and can further improve the factor of safety of the rural soil slopes and river bank control. SF has the potential to serve as a low-carbon alternative reinforcement for a low-height retaining wall structure. This integrated system of transport minimization, additional revenue stream and skill development for farmers as well as carbon footprint reduction promote sustainable rural development. Enhancing soils by utilizing SF aligns more closely with the notion of ecoengineering, considering its economic viability, mass availability and ecological support.

## 5 Conclusion

A mere 1% or lower dosage of SF is found to be optimum for strengthening applications in geotechnical experimental findings. The SF has also demonstrated compatibility as a standalone additive as well as a secondary additive and offers synergistic strength improvements to the geomaterials. Despite the encouraging results, leveraging the material's performance in geosynthetics has not been widely tested on a laboratory scale and in field studies. Simulating the field condition by cyclic and dynamic loadings resulted in enhanced performance of the SF-stabilized soils, highlighting its potential field applications in pavement soil subgrade, liquefaction mitigation and soil reinforcing applications. Natural geosynthetics enhance soil properties while safeguarding the environment from pollution. The utilization of SF contributes to the development of sustainable practices by adding additional commercial value to these fibers. As a component of sustainable development, it is a step in the right direction in the direction of preventing pollution of the soil and the groundwater table.

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