Construction and Building Materials 363 (2023) 129661

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

Natural fibres and biopolymers in FRP composites for strengthening concrete structures: A mixed review

Chinyere O. Nwankwo [a,*], Jeffrey Mahachi [a], David O. Olukanni [b], Innocent Musonda [a]

[a] Center of Applied Research and Innovation in the Built Environment (CARINBE), Faculty of Engineering and the Built Environment, University of Johannesburg, South Africa
[b] Department of Civil Engineering, Covenant University, Nigeria

ARTICLE INFO

Keywords:
Biocomposite
Natural fibre
Biopolymer
Reinforced concrete
Strengthening

ABSTRACT

Fibre-reinforced polymer (FRP) laminates/sheets have been used to retrofit concrete structures. Increased global awareness of environmental protection needs and recent legislation have propelled researchers to develop more environmentally friendly FRP materials to be used in place of synthetic FRP materials. Through a bibliometric and systematic literature review, this article reports on research on the use of bio-based FRP materials comprising of either natural fibres or biopolymers as external reinforcement for concrete structures. Eighty-seven experimental studies retrieved from Scopus and Google scholar databases were considered for this study. Analysis and visualization of research output per year and region, re-occurring keywords, co-authorship network and document co-citation networks are presented. The effects of various bio-based FRP materials used to strengthen various concrete members considering different FRP fabrication techniques and FRP configurations are presented. The study revealed that bio-based FRPs could effectively strengthen concrete beams and columns. Durability, cost and sustainability of these materials are also discussed. The paper also outlines pathways for further research and considerations for developing design frameworks.

1. Introduction

Various reasons such as building change of use, degradation, changes in design codes and correcting design and construction faults create the need to strengthen/retrofit civil engineering structures. Structural strengthening is done conventionally by adding additional structural members (beams, columns or walls), bonding steel plates or concrete jackets to structural members, using external post-tensioning or using fibre reinforced polymer (FRP) laminates or sheets [1,2]. Externally bonded FRP is one of the most common techniques because the material has a high strength to weight ratio, is corrosion resistance and relatively easy to handling and installation [2–4].

The typical FRP is a composite of synthetic fibres (i.e., carbon, glass, asbestos, beryllium, molybdenum, and aramid) and a synthetic polymer matrix (i.e., epoxy, polyester, and vinyl ester). Though the resulting composite is a high-strength, lightweight material used across various industries, it has a high embodied energy and carbon footprint [5]. The production of synthetic fibres consumes large quantities of fossil fuels and is energy intensive [6]. Approximately 300 GJ is required to produce a tonne of carbon fibre, whereas the same quantity of natural hemp fibre requires just 5 GJ [7]. This energy requirement translates to the volume of greenhouse gases released during fibre production. The production of one tonne of carbon fibre gives off about 29,500 kg CO_2; one tonne of glass fibre gives off 1700 – 2500 kg CO_2; whereas natural fibres like hemp, flax, jute and kenaf fibres give off 410, 350, 550 and 420 kg CO_2-eq per tonne of fibre respectively [8]. The production of synthetic FRPs emits toxic by-products, and there are some health hazards associated with certain exposure to them [9–12]. Their disposal also has negative environmental implications because they are often non-recyclable [13]. Since the development of FRPs, there has been a consistent increase in their demand, and the construction industry accounts for 10% of the global FRP demand [14]. They are typically used for non-structural applications like door and window frames, ceiling boards, and partitions and structural applications like internal and external reinforcing material.

Scientists in the building industry are working to develop materials more adaptive to the environment with considerations for a circular economy [15]. The environmental consciousness of global warming has made sustainable development one of the essential considerations in every sector as mankind seeks to prevent further environmental damage

* Corresponding author.
E-mail address: chin9ere@gmail.com (C.O. Nwankwo).

https://doi.org/10.1016/j.conbuildmat.2022.129661
Received 5 August 2022; Received in revised form 2 October 2022; Accepted 1 November 2022
Available online 28 November 2022

[16]. Hence, the environmental impact of building materials from manufacture to disposal is a crucial consideration in material development. Sustainability considerations within the last two decades have fuelled the development of several natural fibre reinforced polymer (NFRP) materials; as of 2021, the construction industry accounted for almost half of the global NFRP market [17]. An FRP composite is termed a biocomposite when a biopolymer (biodegradable polymer) is used as the polymer matrix and is reinforced with natural fibres. Biopolymers can be obtained from natural sources (biomass or micro-organisms) or synthesised from petroleum-based chemicals or bio-derived monomers [18,19]. Though more researchers in recent times are developing biocomposites for their environmental advantage and low cost [20] for various applications, there are currently limited studies on biocomposites as external structural reinforcing material. There is a need to assess the current body of work in using natural fibres and biopolymers in developing FRP composites materials used for strengthening concrete structures and identify pathways for further studies. This study aims to review various experimental studies on the application of bio-based FRP for strengthening concrete structures by; (1) retrieving available literature on FRP composites made with natural fibres and biopolymers used specifically as external structural reinforcement; (2) Assessing the research output per year and country, author networks, and research trends; (3) synthesize the findings in the available literature; (4) identify some research gaps and future potential research directions.

2. Methodology

A systematic literature review guided by the PRISMA 2020 statement was conducted for this study [21]. A bibliometric analysis of the retrieved articles involving keyword co-occurrence analysis and author co-citation network was done. An analysis of the number of publications per year and country and main publication sources were also outlined. Manual analysis was done with search results to identify the significant findings.

2.1. Data set retrieval and filtration

Documents were retrieved from Scopus and Google Scholar databases [22]. The search query, natural AND fibre OR fiber AND reinforced AND concrete AND strengthening, was used on Scopus (accessed on 4th April 2022), and 198 documents were retrieved. The search returned 38,400 results on google scholar (assessed on 23rd May 2022), but relevant documents were contained within the first 200 results and were considered for further assessment. An additional 232 documents were retrieved from Scopus with the revised search query “natural fiber reinforced polymer” OR “natural fibre reinforced polymer” AND “reinforced concrete” AND strengthening AND beam OR slab OR column OR wall (assessed on 1st June 2022).

The title and abstract of the retrieved documents were screened and documents solely based on carbon, glass and basalt FRP were excluded from the search. Also, documents based solely on the development of NFRP composites but not used in strengthening any structural members were excluded. Reviews and conference titles were excluded from the assessment. The reviewed documents were strictly experimental studies in which bio-based FRP with natural fibres or biopolymers were developed and used to strengthen structural members. All the documents obtained were not limited to any period to understand the development of the research area over time. After further analysis of the selected documents was done, seven documents were excluded as they had research data already presented in a different paper by their author that was already considered. Eleven additional relevant documents were retrieved from citation searches of the identified papers. Fig. 1 outlines the document selection process. A final 87 documents were considered for the study. Twenty-two documents were conference papers, while 65

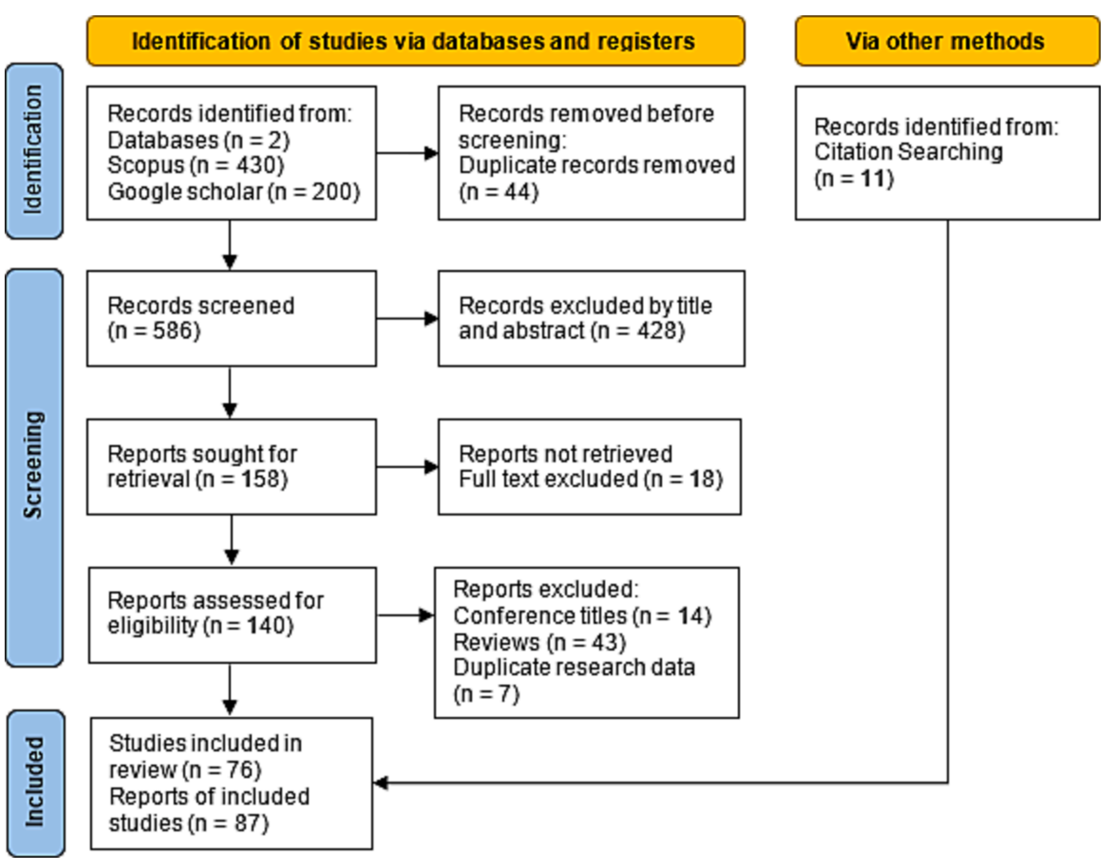

Fig. 1. Document selection process.

were journal articles.

35 of 198 documents and 38 of 232 documents from Scopus with the first and second search query respectively and 47 of 200 documents from Google scholar met the inclusion and exclusion criteria. All the documents were manually checked to identify duplicates with Microsoft Excel. Fig. 2 shows the number of documents retrieved from the considered sources and search criteria and how they overlap.

2.2. Analytical tools

VOSViewer (version 1.6.18), a free, open-source visualisation computer program, was used to analyse and visualise the reoccurring keywords and author co-citation network. The publications per year and country analysis were gotten from SCOPUS, and the data from the eight documents not contained in the SCOPUS database was entered manually in Microsoft Excel.

3. Results of bibliometric analysis

3.1. Publication output

Fig. 3 presents the output per year of the 87 documents considered for this study. The graph shows that the study on using bio-based FRPs as external structural reinforcement is a recent development, as research has only existed in this area within the last decade. This area is still emerging, but its development has been enhanced by increased global warming concerns, progressive government legislature encouraging the development of more eco-friendly materials, and increased prices of non-renewable petroleum resources [23].

The first document available was published in 2012. Since 2017, there has been a steady rise in research output in this area. The highest number of publications recorded in a single year was 18 documents in 2021. It is noted that 2022 is a half year, and not all documents that would exist in this year have been published yet.

The document sources were also analysed to identify the journals with significant impacts in the field. The documents considered for this study were published in 48 sources. Table 1 highlights the top sources with a minimum of three publications and the corresponding year of the latest publication. The construction and building materials journal had the most publications in the research area, with 11 publications, followed by the materials and structures journal. This information can potentially guide future researchers to source relevant published research and target their research.

3.2. Publication by country

The country-wise publication provides an outlook on this research trend by world regions. The review found that south and eastern Asian countries with Thailand, India, Malaysia and China have the highest publication output in this area. New Zealand is also a leading country in this research area, with 14 documents. Fig. 4 below provides the outlook of the publication output by country. The data presented was limited to countries with more than one output. Other countries not represented in the graph with just one output include Australia, Brazil, Canada, Ethiopia, Hong Kong, Indonesia, Italy, Pakistan, Peru, South Korea, Turkey and the United Kingdom. The distribution of the research output by continent is Asia (79), Europe (19), Oceania (15), Africa (8), North America (4) and South America (2).

The interest in developing bio-based composites in certain regions can be attributed to the types of crops produced in such regions. The major natural fibre source crops [24] are presented in Table 2. Asia has conducted the most research in developing bio-based composites and is also the leading producer of these natural fibre source crops. Though Europe had the second least production, it still had the second largest publication output in the research area. Legislations and government policies can help increase bio-based FRP materials' development. Legislation was created in the European Union (EU) and some Asian countries that encouraged the use of natural fibres in the automobile industry [25]; there also has been increased funding by the EU to develop NFRP composites that can be used by the aerospace industry [26]. Following Europe and Asia, other regions can be more deliberate in using their locally available crops to produce more bio-based

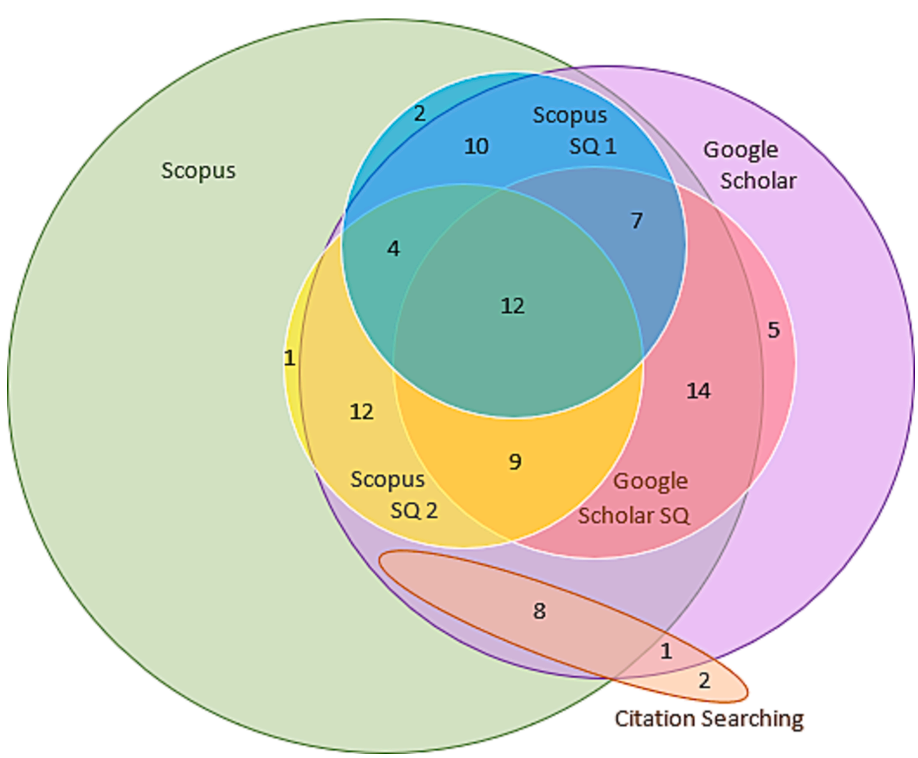

Fig. 2. Venn diagram showing the overlap of relevant documents returned from search queries (SQ) in Scopus and Google Scholar databases.

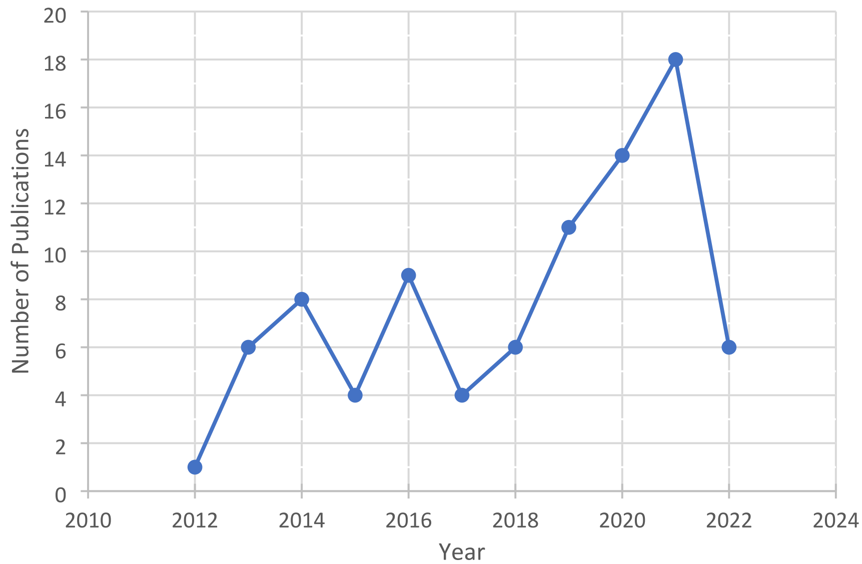

Fig. 3. Number of publications by year.

Table 1
Top document sources.

Source	Publications	Latest Publication
Construction and Building Materials	11	2022
Materials and Structures/Materiaux et Constructions	5	2021
Composite Structures	4	2021
Composites Part B Engineering	3	2017
IOP Conference Series: Materials Science and Engineering	3	2020
Materials	3	2020
Materials Science Forum	3	2016
Materials Today: Proceedings	3	2020

composites.

3.3. Keyword analysis

Keyword analysis presents an outlook of the research trend within a study area. VOSviewer was used to present a density visualisation of the re-occurrence of keywords in the considered documents. The bibliometric data was cleaned to prevent separate calculations of the keywords “fibre” and “composite” in different linguistic forms (i.e., fibres, fiber, fibers and composites). The minimum number of keyword occurrences was set to 3, and of the 225 keywords recognised, 29 met the threshold. Of all the keywords identified, the keywords with a minimum of six occurrences from the highest are natural fibre, concrete, confinement, compressive strength, strengthening, ductility, reinforced concrete, flexural strengthening and shear strengthening. The keyword density visualisation is presented in Fig. 5.

3.4. Co-Authorship network

Co-authorship network helps identify the leading authors and their networks in this field. Analysis was done with bibliographic data from both Scopus and Google scholar, and VOSviewer was used to analyse and present the data. The minimum number of author occurrences was set to 3; of the 213 authors recognised, 28 met the threshold. Eight research clusters can be observed from the co-authorship network shown in Fig. 6. The colours depict the average number of citations per document, and the number of documents is directly related to the size of

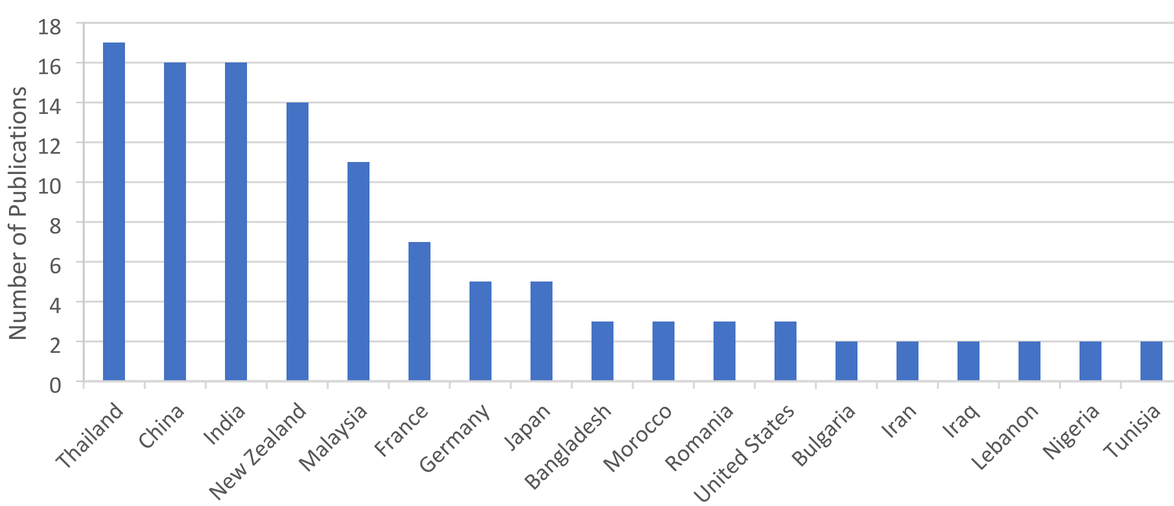

Fig. 4. Number of publications by country.

Table 2
Total production of major natural fibre source crops by continents from 2010 to 2022.

Plant Fibre Crop	Total Production of Plant Fibre Crops (Million Tonnes)					
	Africa	N.America	S.America	Asia	Europe	Oceania
Abaca, manila hemp, raw	0.003 (0.28 %)	0.000	0.393 (34.24 %)	0.751 (65.48 %)	0.000	0.000
Coir, raw	0.460 (0.87 %)	0.000	39.817 (75.17 %)	12.691 (23.96 %)	0.000	0.000
Cotton lint, ginned	15.978 (6.48 %)	36.904 (14.97 %)	19.724 (8.00 %)	163.414 (66.28 %)	3.475 (1.41 %)	7.061 (2.86 %)
Flax, processed but not spun	0.090 (1.23 %)	0.000	0.061 (0.83 %)	0.288 (3.95 %)	6.860 (93.99 %)	0.000
Jute, raw or retted	0.092 (0.25 %)	0.000	0.010 (0.03 %)	36.035 (99.72 %)	0.000	0.000
Kenaf, and other textile bast fibres, raw or retted	0.183 (7.22 %)	0.000	0.181 (7.17 %)	1.623 (64.18 %)	0.542 (21.42 %)	0.000
Ramie, raw or retted	0.000	0.000	0.003 (0.30 %)	1.150 (99.70 %)	0.000	0.000
Sisal, raw	0.894 (33.16 %)	0.000	1.639 (60.83 %)	0.162 (6.02 %)	0.000	0.000
True hemp, raw or retted	0.000	0.000	0.047 (2.27 %)	0.747 (36.14 %)	1.273 (61.59 %)	0.000
Total	17.699 (5.02 %)	36.904 (10.47 %)	61.876 (17.55 %)	216.862 (61.51 %)	12.149 (3.45 %)	7.061 (2.00 %)

Sources: [27].
Note: Values in parenthesis represent the percent production of each continent.

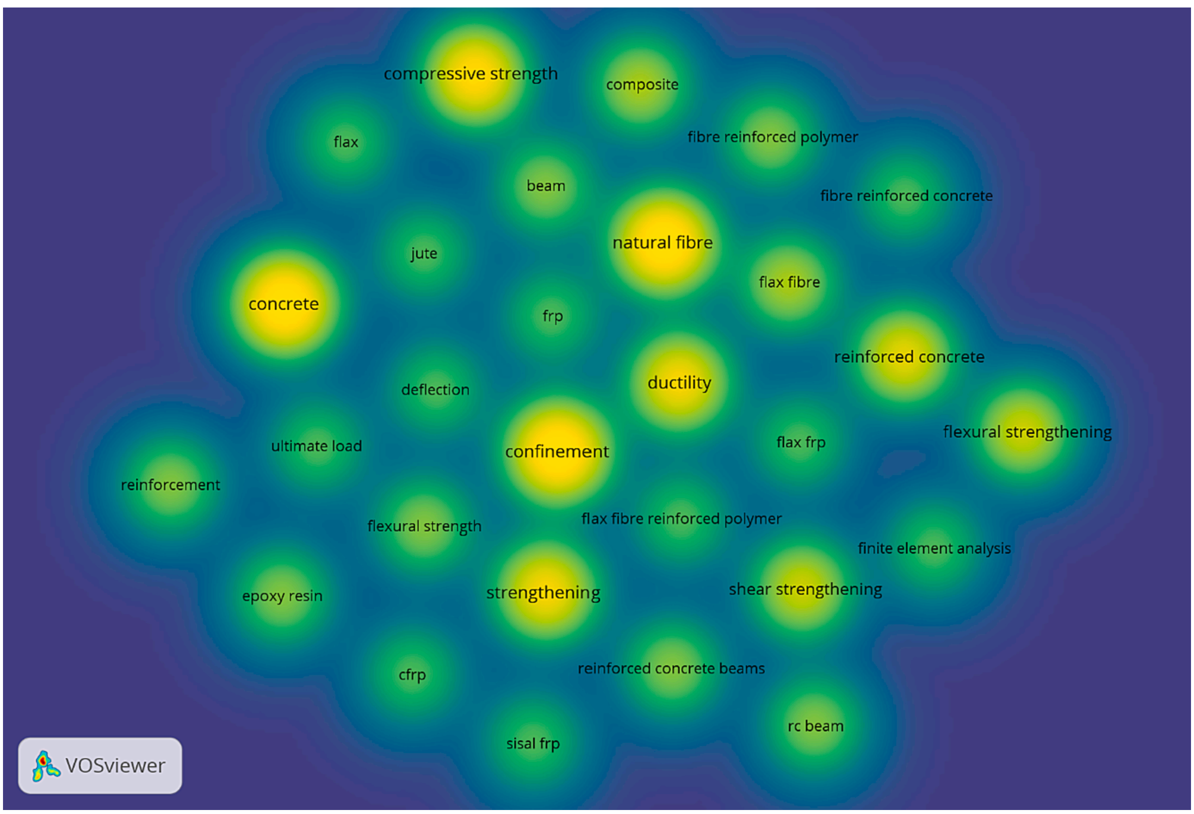

Fig. 5. Keyword analysis.

the bubbles. The leading researchers in this field are Chown N., Yan L., Hussain Q., Reddy H.N.J. and Pimanmas A.

3.5. Document Co-Citation network

A document co-citation analysis was carried out to understand the conceptual structure of this research area. The document co-citation network is presented in Fig. 7. It displays the interconnection of the most co-cited publications across the retrieved documents. The minimum number of 'citations of a cited reference' was set to 7 for this mapping. Six hundred eighty-four duplicate references were identified using Microsoft Excel and a thesaurus file was added to the VOSviewer database to merge synonymous references. One thousand seven hundred forty-five cited references were identified, and 37 documents met the threshold set. Three evident clusters were formed. The red cluster had research themes about concrete columns confined with carbon fibre reinforced polymer (CFRP) and documents on the codes guiding FRP material testing and usage. The green cluster had publication around FRP usage for strengthening concrete beams and columns. The blue cluster had research output on precast NFRP tubes for circular beams and columns.

4. Research progress

4.1. Bio-Based FRP materials

An FRP composite is primarily made of a matrix material and a reinforcement material. The FRP composite is bio-based when either a natural fibre or biopolymer is used.

4.1.1. Natural fibres used in Bio-Based FRP strengthening systems

The reinforcing component in FRPs is mostly in the form of fibres, and it carries 70–90 % of the load applied to the composite; it invariably establishes the strength and stiffness of the composite [13,28,29].

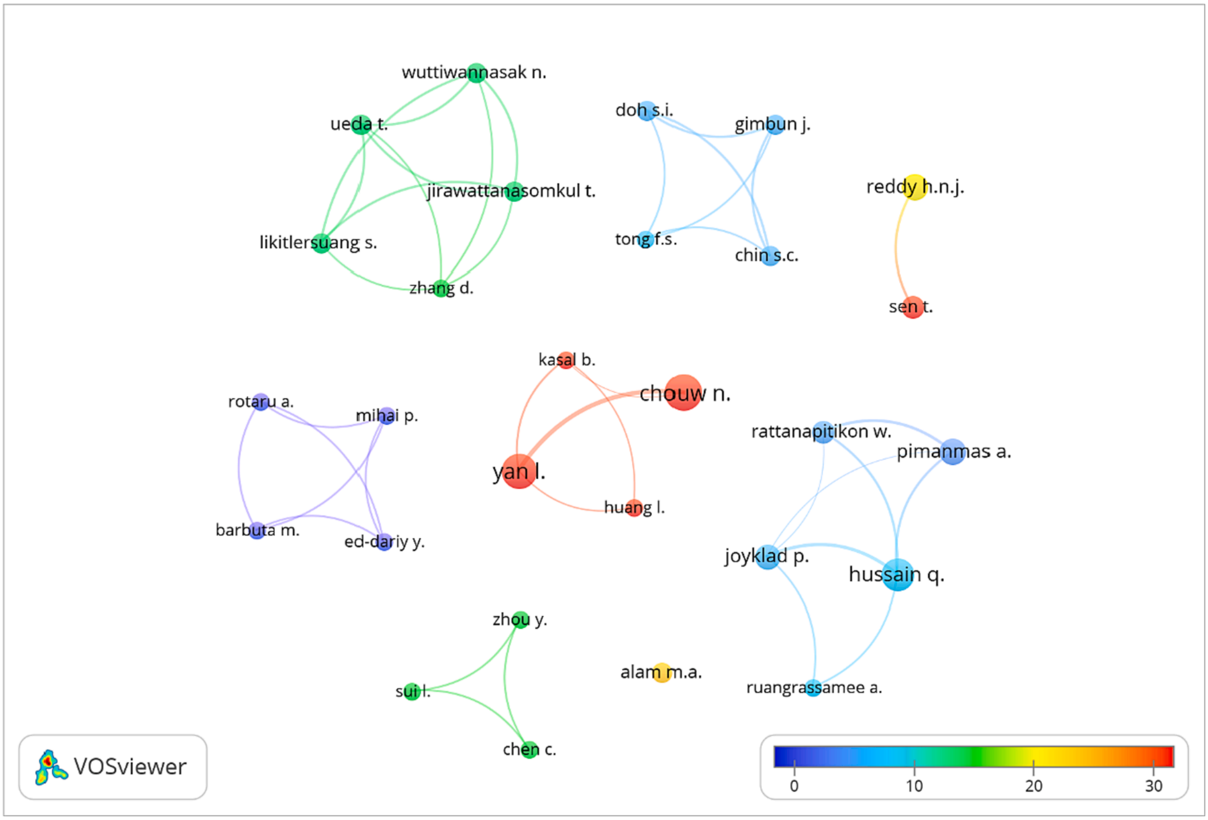

Fig. 6. Citation links across countries visualising research output and citation/document count.

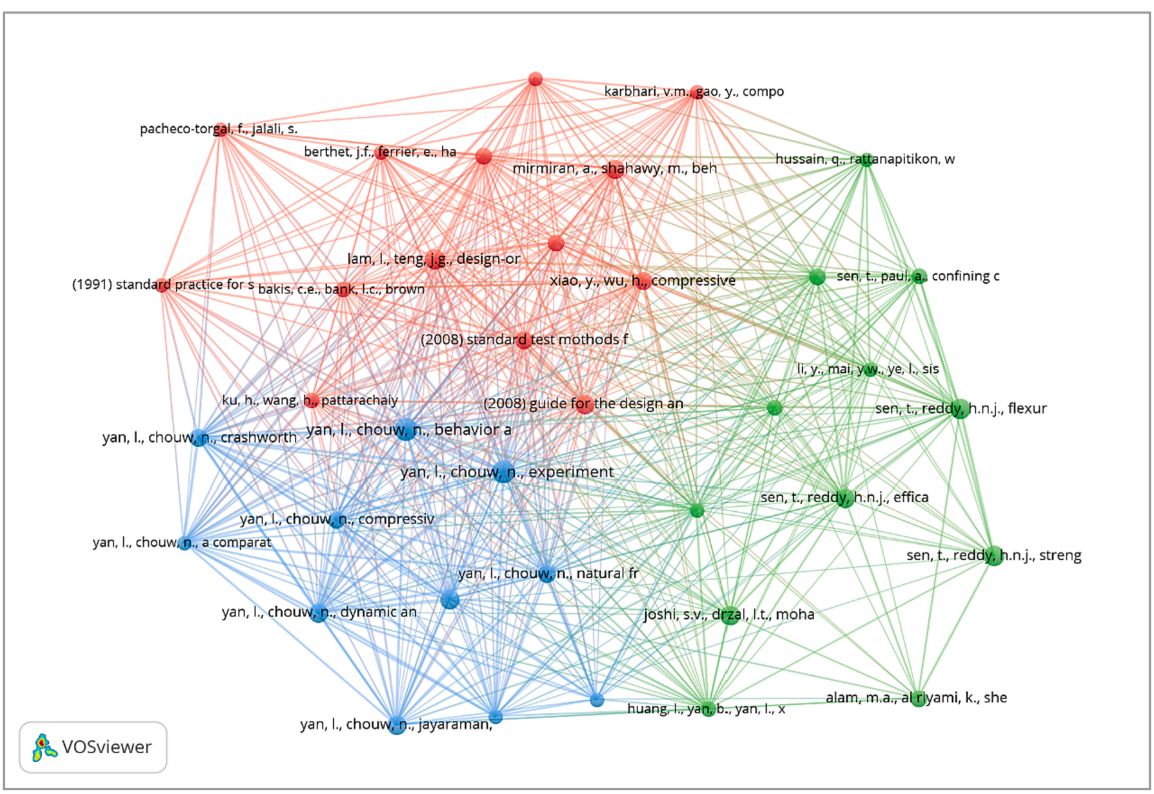

Fig. 7. Citation links across countries visualising research output and citation/document count.

Natural fibre as the reinforcing material in FRP composites has received much attention because of its non-toxicity, low density, biodegradability, easy accessibility, cost and renewability [30]. However, issues relating to the variability of fibre properties and the un-standardization of processing the fibres from extraction to processing have limited their usage [31,32]. Also, natural fibres are hydrophilic; as they absorbed moisture, their bond with the polymer matrix is weakened. This compromises the mechanical performance of the overall material and also makes it more susceptible to microbial attacks and decomposition [30,33]. Various chemical and mechanical treatments can minimise the water absorption tendencies of natural fibres and enhance their adhesion with the polymer matrix.

Fig. 8 presents the natural fibre types used in the research works considered for this review. Flax fibre was the most used natural fibre in bio-based FRPs for structural strengthening followed by jute, hemp, sisal, kenaf, cotton, bamboo and coir. Other fibres like abaca, alfa, banana, hibiscus vitifolius stalk, mengkuang, pineapple leaf and water hyacinth fibre were not included in the graph but had one occurrence. Fig. 8 also presents the corresponding midrange tensile strength of the fibres as presented in [34]. The superior performance of flax has made it the most used fibre.

This review was limited to natural organic derived fibres, so this study did not consider natural fibres derived from inorganic mineral sources like basalt. Though basalt fibre is eco-friendly and non-toxic, its production requires specialised processes [35–37] and is energy-intensive relative to natural fibres from other sources.

Aside from fibre type, fibre orientation and form can significantly affect the strength and performance of the resulting FRP material [38]. Fibres are anisotropic and have their maximum strength in the longitudinal direction; so they are optimal when they are laid to provide the greatest resistance to the failure surface [39]. Unidirectional fabrics have their fibres predominately in one direction, while bidirectional fabrics have fibres in two perpendicular directions. FRP composites with unidirectional fibres oriented in the 0° direction have superior static mechanical properties to those with bidirectional fibres with the same fibre content [40]. Woven bidirectional fibres creates an isotropic material with similar mechanical properties in biaxial loading directions [41].

4.1.2. Polymer matrix used in NFRP strengthening systems

The matrix component of an FPR material defines the shape of the material; receives the loads placed on the material; bonds the fibre reinforcement together, making a rigid composite; guards the fibres against chemical and mechanical damage; provides an excellent surface finish; controls the ductility of the material; isolates the fibres so they can act individually; curtails crack propagation; and with its rigid structure, absorbs induced vibrations [13,28,42]. Polymer matrix composites are typically used for structural retrofitting. This composite system combines the high strength of fibres with the bonding properties of polymers to produce an engineering composite [13]. Fig. 9 presents an overview of the various polymers used in developing structural bio-based FRP materials. Epoxy is the most used polymer, accounting for 87.9 % of the polymer matrix used in the reviewed literature. Polyester, vinyl-ester and bio-based epoxy represent 6.5 %, 3.2 % and 3.2 % of the total. Of all the publications reviewed, only three studies used a bio-based resin [3,43,44].

4.2. Structural members strengthened

FRPs when used as external reinforcement for structural rehabilitation and repair are typically wrapped around concrete columns and bonded to the soffit and sides of structural beams, slabs and walls. Fig. 10 presents the distribution of structural members strengthened with NFRP composite materials. Reinforced concrete (RC) beams and concrete columns were the most member type strengthened with bio-based FRP, with research considering these member types accounting for 40% and 37%, respectively. Concrete beams [45–56] and RC columns [57,58] represented 14% and 2% of the members strengthened. RC slab [59], concrete slab [60], RC wall [61], masonry brick [62], masonry wall [63] and wood laminated beam [64] had a single occurrence. It is essential to state that reinforced concrete was included in the search query, so more research with other material types may exist other than the numbers presented here.

4.2.1. RC beams strengthened with bio-based FRP

Bio-based FRPs have been used to strengthen RC beams in various conditions including regular rectangular beams, pre-damaged beams [65], beams with corroded reinforcement [66,67], beams with insufficient reinforcement [67–70], beams with openings [71], deep beams [65,72,73] and post-tensioned beams [74,75].

4.2.1.1. FRP fabrication type. When Bio-based FRP is used to strengthen an RC beam , it is either laid on the beam directly by the wet lay-up process or is built-up independent (precured) from the member to be strengthened and later attached to the member with a suitable resin material. When successive layers of fibre and polymer are built-up, the developed composite is a laminate/plate. The wet lay-up process allows for a more flexible construction process but could give more room for inconsistent results. Since the fibres/fabrics are typically impregnated with the polymer matrix on site, it is difficult to determine the exact

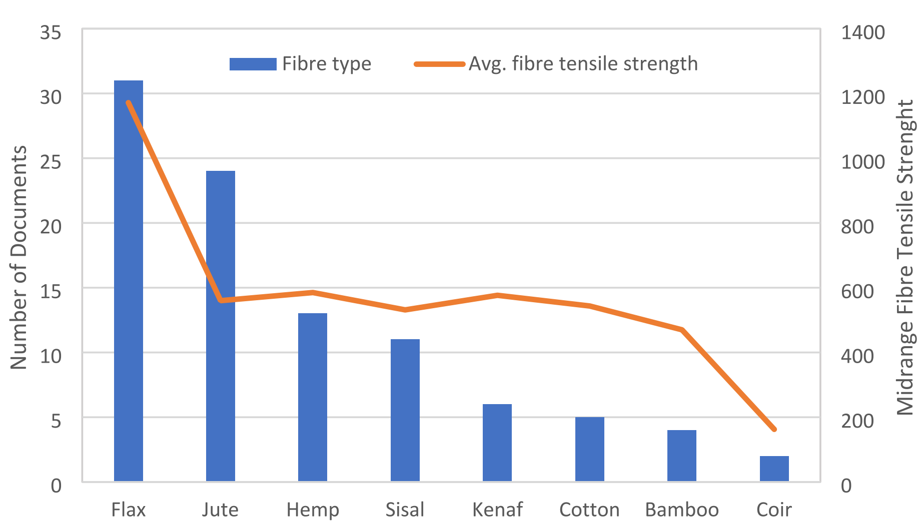

Fig. 8. Fibre used in bio-based FRP strengthening systems.

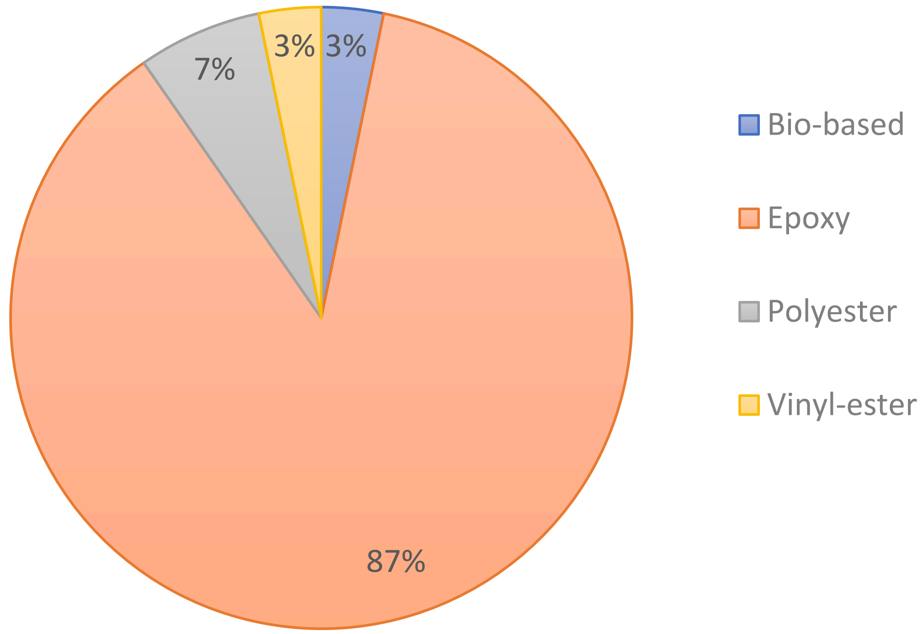

Fig. 9. Polymer used in bio-based FRP strengthening systems.

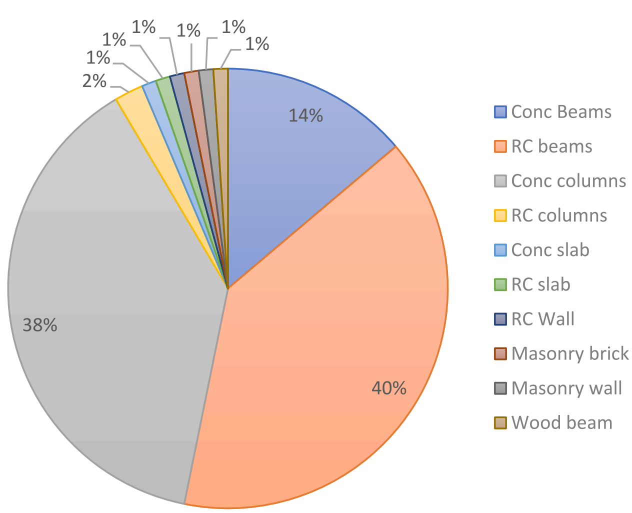

Fig. 10. Distribution of Structural Members strengthened with bio-based FRP.

quantity of resin used; thus, the strength of the built-up laminate may not be accurately determined [76]. Precured FRP typically has a larger thickness and more polymer content [77].

4.2.1.2. FRP configurations. The placement of FRPs on RC beams is referred to as the FRP-beam configuration (FRP-beam config). The configuration in which the FRP material is attached to the beam controls the beam actions that are complemented i.e., flexure, shear or torsion. The different configuration types in the considered documents are schematically presented in Fig. 11. The number by each half-beam corresponds to the FRP-beam configuration type in Table 3. It can be observed from Table 3 that configuration type affects the FRP strengthening effect.

4.2.1.3. Beam failure modes. The design development of bio-based FRP laminates as a structural retrofitting material will require an understanding of various failure modes associated with its use [78]. A schematic depiction of the failure modes of an RC beam retrofitted with an FRP laminate in flexure as described by [79] is presented in Fig. 12. Failure modes RC_1 (concrete crushing), RC_2 (shear failure) and RC_3 (flexural failure) are related to the typical RC beam failures. FRP

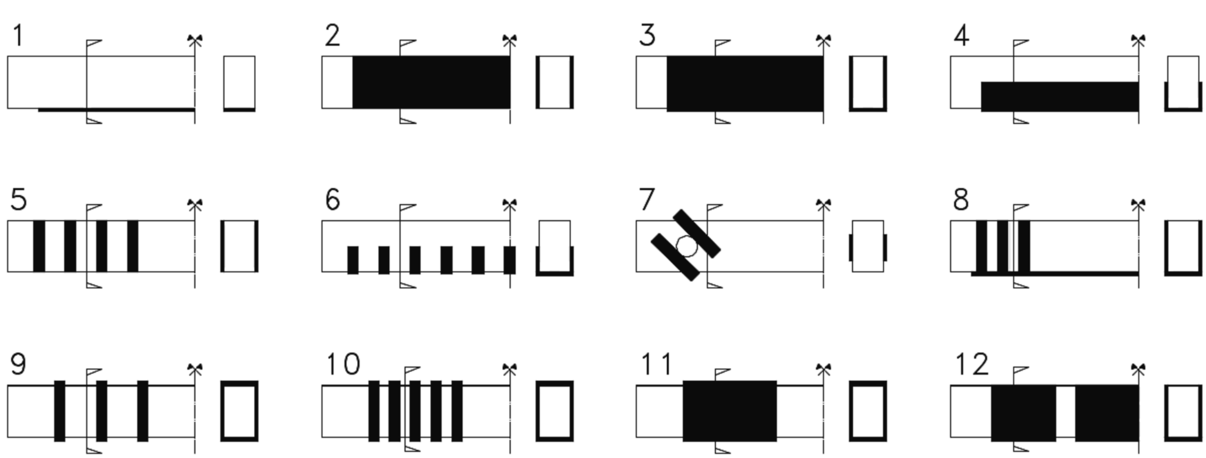

Fig. 11. Beam-FRP configurations.

Table 3
Bio-based parameters and strengthening effects on RC beams.

S/N	Bio-based FRP Material Components and Fabrication Type: Fibre type	Fibre form	Polymer	Fabrication type	RC beam Properties: Beam width, height, length (clear span); test type (mm)	Cube conc. comp. strength (MPa)	Bio-Based FRP Material Properties: Tensile strength (MPa)	Young's Modulus (GPa)	Strain (%)	FRP -beam Config	Number of layers/ Thickness (mm)	Increased Capacity (%)	Failure Mode	Ref.
1.	Hemp	Bidirectional Fabric	Epoxy – Smart Cf-Resin	Wet lay-up	100 × 300 x 900 (750); 3P	27	156	6.414	0.51	2	1	29.1	RC_2	[72]
										3	1	31.9	RC_2	
										2	2	48.0	RC_2 + D	
										3	2	45.8	RC_2	
2.	Flax	Unidirectional fibres	Epoxy	Wet lay-up	150 × 250 × 2400 (2100); 3P	41.32 ± 2.98	123.0 ± 6.43	5.76 ± 0.56	2.00 ± 0.18	1	4/1.80 mm	34.4	FRP^r	[84]
							75.57 ± 3.67	4.81 ± 0.39	1.55 ± 0.11		6/3.28 mm	32.7	FRP^r	
							69.69 ± 5.60	4.30 ± 0.25	1.43 ± 0.20		8/4.46 mm	37.2	Cc_3^{sp}	
	Jute	Bidirectional fabric	Epoxy	Wet lay-up			43.41 ± 0.44	2.60 ± 0.07	1.62 ± 0.01	1	2/4.34 mm	15.7	FRP^r	
							45.19 ± 1.96	2.67 ± 0.05	1.61 ± 0.01		4/8.89 mm	54.9	FRP^r	
							47.65 ± 2.16	2.59 ± 0.09	1.69 ± 0.06		6/11.9 mm	50.7	Cc_2^{mid} + FRP^r	
3.	Jute	Bidirectional fabric (347 g/m^2)	Epoxy – Lica-100	Wet lay-up	150 × 250 × 2400 (2100); 4P	41.32 ± 2.98	35.28 ± 4.96	2.03 ± 0.13	1.83 ± 0.17	1	2/3.81 mm	17.3	FRP^r	[85]
		Bidirectional fabric (719 g/m^2)					39.24 ± 3.02	1.42 ± 0.09	2.69 ± 0.30		3/3.87 mm	−0.6	FRP^r	
	Flax	Bidirectional fabric	Epoxy – Lica-100	Wet lay-up			55.99 ± 0.34	1.34 ± 0.05	3.75 ± 0.19	1	4/6.01 mm	18.0	FRP^r	
		Unidirectional fibre					123.0 ± 6.43	5.76 ± 0.56	2.00 ± 0.18		8/8.68 mm	40.5	Cc_1^{mid} + FRP^r	
4.	Jute -Basalt	Bidirectional fabric	Epoxy	Wet lay-up	150 × 300 × 2800 (2500); 4P	20.4				1	4	24.5	Cc_1^{mid} + FRP^r	[91]
										4	4	39.6	FRP^r	
5.	Kenaf	Unidirectional fibres (34 % wfc)	Epoxy – Epotec YD 127	Precured	125 × 240 × 1840 (1690); 4P	51.62[a]				1	13 mm	81.8	Cc_5^{end}	[76]
6.	Flax	Unidirectional fibres	Epoxy	Wet lay-up	150 × 250 × 2400 (2100); 4P	41.3 ± 1.9	123 ± 16.6	5.8 ± 0.7		1	4	33.0	FRP^r	[87]
											6	32.7	FRP^r	
											8	36.4	FRP^r	
				Precured			252 ± 15.2	10.5 ± 0.5			6	37.5	FRP^r	
7.	Kenaf	Unidirectional fibres (44 %wfc)	Epoxy	Precured	150 × 300 × 2300 (2000); 4P	32[a]	136	14.91		5	6 mm	9.6	RC_3	[92]
	Jute	Unidirectional fibres (45 % wfc)	Epoxy	Precured			137	14.79			6 mm	23.1	RC_3	
	Jute	Unidirectional ropes (44 % wfc)	Epoxy	Precured			113	10.37			6 mm	30.7	RC_3	
8.	Hibiscus vitifolius stalk	Bidirectional fabric	Epoxy	Precured	3000 (2800); 4P	30				1	1	6.05		[93]
											2	16.9		
											3	40.7		
											4	30.6		
9.	Sisal	Unidirectional braided fibres into fabrics	Epoxy	Wet lay-up	120 × 180 × 1460 (1260); 3P	35[a]	80 ± 0.02	3.02 ± 0.01	3.65 ± 0.04	1	2	19.2	Cc_2^{mid}	[50]
											2 w/ anch.	44.5	RC_2	
											4 w/ anch.	67.8	RC_2	
			Polyester	Wet lay-up			104 ± 0.03	3.19 ± 0.04	3.48 ± 0.02		2	13.8	Cc_3^{sp}	
											2 w/ anch.	28.6	RC_2	

(*continued on next page*)

Table 3 (*continued*)

S/N	Bio-based FRP Material Components and Fabrication Type: Fibre type	Fibre form	Polymer	Fabrication type	RC beam Properties: Beam width, height, length (clear span); test type (mm)	Cube conc. comp. strength (MPa)	Bio-Based FRP Material Properties: Tensile strength (MPa)	Young's Modulus (GPa)	Strain (%)	FRP -beam Config	Number of layers/ Thickness (mm)	Increased Capacity (%)	Failure Mode	Ref.
											4 w/ anch.	35.7	RC_3	
10.	Bamboo (40 % vfc)	Unidirectional braided fibres	Epoxy	Precured	100 × 130 × 1600 (1400); 4P	30	64.5		≈ 2.7	1	6 mm	10.4 (ST-B1)	RC_2	[94]
11.	Sisal	Unidirectional fibres	Epoxy	Wet lay-up	200 × 200 × 1200; 4P	M20				3	2	26.2		[95]
						M25						18.5		
						M30						26.2		
						M35						22.8		
	Coir	Unidirectional fibres	Epoxy	Wet lay-up		M20					2	40.5		
						M25						33.4		
						M30						31.0		
						M35						23.2		
12.	Jute	Bidirectional fabric (24 % vfc)	Epoxy	Wet ay-up	150 × 300 × 1200 (900); 3P	38.7[a]	203 ± 15	14.485 ± 0.88	2.2 ± 0.1	3	2	−11.5	RC_2 + FRP^r	[65]
											4	6.8	RC_2 + FRP^r	
13.	Hemp	Unidirectional fibres	Epoxy	Wet lay-up	100 × 300 × 900 (750); 3P					2	1	34.2		[73]
										3	1	27.9		
		Bidirectional fabric								2	2	11.6		
14.	Sisal	Bidirectional fabric	Epoxy – MBrace Sat.	Wet lay-up	140 × 200 × 1400 (1300); 4P	22.31	223			4	1	77.8	RC_2 + FRP^r	[96]
										6	1	33.4	RC_2	
15.	Hemp	Bidirectional fibres (0°90° & −45°+45°)	Bio - derived resin	Precured	152 × 152 × 2438 (2334); 4P	37.92[a]	1170	72.39	1.02	1	10/6.35 mm	68	RC_3 + FRP^r	[3]
16.	Sisal	Bidirectional fabric	Epoxy – MBrace Sat.	Wet lay-up	140 × 200 × 1400 (1300); 4P	22.31	223.37			4	1	112.5	RC_3 + FRP^r	[89]
										6	1	65.2	RC_3	
17.	Jute	Bidirectional fabric	Epoxy – MBrace Sat.	Wet lay-up	140 × 200 × 1400 (1300); 4P	22.31	189.48	32.5		4	1	62.5	RC_3 + FRP^r	[97]
										6	1	25	RC_3	
18.	Jute	Bidirectional fabric	Epoxy – MBrace Sat.	Wet lay-up	140 × 200 × 1400 (1300); 4P	22.31	189.48	32.5		4	1	67	RC_2 + FRP^r	[6]
										6	1	22	RC_2	
19.	Jute	Bidirectional fabric	Epoxy – Sikadur 31	Wet lay-up	150 × 150 × 1000 (900); 3P	30				1	1 (50 mm wide)	5.6		[98]
											2 (50 mm wide)	≈ 8.9		
				Wet lay-up							1 (100 mm wide)	5.6		
											2 (100 mm wide)	≈ 10.0		
				Wet lay-up							1 (150 mm wide)	11.1		
											2 (150 mm wide)	≈ 20.8		
20.	Kenaf	Unidirectional fibres (25 %wfc)	Epoxy	Precured	150 × 300 × 2300 (2000); 4P	32	119.6	11.7		5	6 mm	32.9	RC_2 + FRP^r	[90]
21.	Bamboo	Unidirectional fibres (40 %vfc)	Epoxy	Precured	120 × 300 × 1500 (1300); 4P	30	≈ 104.6			7	8 mm	54.3	RC_2	[71]
			polyester				≈ 85.4				6 mm	61.4	RC_2	
			Vinyl ester				≈ 78.0				8 mm	74.3	RC_2	
22.	Jute	Unidirectional ropes (25 %wfc)	Epoxy – BBT-7892	Precured	125 × 250 × 2300 (2000); 4P		99.97			1	8 mm w/ anch.	63.2	Cc_1^{mid}	[83]

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Table 3 (*continued*)

S/ N	Bio-based FRP Material Components and Fabrication Type: Fibre type	Fibre form	Polymer	Fabrication type	RC beam Properties: Beam width, height, length (clear span); test type (mm)	Cube conc. comp. strength (MPa)	Bio-Based FRP Material Properties: Tensile strength (MPa)	Young's Modulus (GPa)	Strain (%)	FRP -beam Config	Number of layers/ Thickness (mm)	Increased Capacity (%)	Failure Mode	Ref.
23.	Kenaf	Unidirectional fibres (40 %vfc)	Epoxy	Precured	100 × 130 × 1600 (1400); 4P	35	78	36		1	6 mm	≈38.8	FRP^{r}	[80]
			Polyester				77	13		1	6 mm	≈37.7	FRP^{r}	
			Vinyl ester				79	15		1	6 mm	≈37.7	FRP^{r}	
24.	Jute	Bidirectional fabric	Epoxy – MBrace Sat.	Wet lay-up	230 × 300 × 3000 (2100); 4P	43.34				3	1	22.9	RC_3 + FRP^{r}	[74]
										6	1	10.0	RC_3	
25.	Abaca	Bidirectional fabric (22 %vfc)	Polyester – Yukalac	Precured	150 × 300 × 2200 (2000); 4P	≈ 41.86	54.58	3.47	1.58	5	1	9.78	RC_2	[68]
										5	2	9.92	RC_2 + D	
26.	Mengkuang leaves	Unidirectional fibres (30 %vfc)	Epoxy – D.E.R. 331	Precured	100 × 130 × 1600 (1400); 4P	25				1	8 mm	13.0	P^{end}	[81]
27.	Flax	Bidirectional fabric (300 g/m^2)	Epoxy – JN-C3P	Wet lay-up	150 × 300 × 1200 (1400); 4P	31.4	94.2	10.3	1.91	8	4	67.8	Cc_1^{mid} + FRP^{r}	[99]
							84.4	10.6	1.71	8	6	105.2	Cc_1^{mid} + FRP^{r}	
28.	Hemp	Fiber ropes	Epoxy	Wet lay-up	120 × 150 × 1500 (1300); 4P	18	177		0.23	9	2	50.1	RC_1	[70]
										10	2	57.2	RC_1	
										11	2	63.2	RC_1	
	Cotton	Fiber ropes	Epoxy	Wet lay-up	120 × 150 × 1500 (1300); 4P	18	129		0.25	9	2	35.8	RC_2	
										10	2	52.0	RC_1	
										11	2	56.1	RC_1	
29.	Jute	Unidirectional fibres	Epoxy	Precured	100 × 150 × 1200 (1000); 4P	25 ± 0.85[a]				1	6.25 mm	40	RC_2	[66]
30.	Jute	Bidirectional fabric	Epoxy	Wet lay-up	110 × 150 × 1460 (1260); 3P	25				1	2	23.9	RC_1	[100]
										4	2	28.3	RC_1	
31.	Kenaf	Unidirectional fibres (47 % wfc)	Epoxy	Precured	150 × 300 × 2000 (1800); 4P	30[a]	146	14.55	24	5	7.5 mm (20 mm wide)	27.6	FRP^{r} + RC_1	[86]
							123	12.29	22	5	7.5 mm (30 mm width)	27.6	RC_1 + RC_1	
							124	12.72	22.2	5	7.5 mm (35 mm width)	35.3	RC_1 + RC_1	
32.	Flax fibre	Bidirectional fabric	Epoxy – JZ-A	Wet lay-up	200 × 400 × 1800 (1240); 3P	38.2 ± 0.3				12	3 (warp dir)	49.5	RC_2 + FRP^{r}	[69]
											6 (weft dir)	47.9	RC_2 + FRP^{r}	
											3 (warp dir w/nano-TiO2)	72.8	RC_2 + FRP^{r}	
33.	Pineapple leaf	Unidirectional fibres (40 % vfc)	Epoxy	Precured	100 × 130 × 1600 (1200); 4P	25				1	6 mm	7.3	P^{end}	[82]
34.	Bamboo	Unidirectional fibres	Epikote 816 resin	Precured	300 × 300 × 1200 (1050);4P					1		26.7		[67]
35.	Hemp	Unidirectional fibre filaments	Epoxy	Wet lay-up	150 × 250c 2700 (2400); 4P					1	1	20.0	FRP^{r} + RC_2	[101]
											2	44.4	FRP^{r} + RC_2	
										3	1	48.8	FRP^{r} + RC_2	
											2	115.6	FRP^{r} + RC_2	

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Table 3 (*continued*)

S/N	Bio-based FRP Material Components and Fabrication Type: Fibre type	Fibre form	Polymer	Fabrication type	RC beam Properties: Beam width, height, length (clear span); test type (mm)	Cube conc. comp. strength (MPa)	Bio-Based FRP Material Properties: Tensile strength (MPa)	Young's Modulus (GPa)	Strain (%)	FRP -beam Config	Number of layers/ Thickness (mm)	Increased Capacity (%)	Failure Mode	Ref.
36.	Sisal	Unidirectional fibre mats	Epoxy	Wet lay-up	150 × 250c 2700 (2400); 4P	24.5	75			1	1 2	29.6 37.7	FRP[r] D	[102]
37.	Sisal	Unidirectional fibres (25 % vfc)	Epoxy –Nitowrap 410	Precured	200 × 200 × 2000 (1800); 4P	M40				1	1 2 2 w/ anch.	27.0 16.2 21.6		[75]

[a] Cylinder compressive strength vfc – volume fibre content wfc – weight fibre content 3P – 3-point bending 4P – 4-point bending w/ anch. – with anchorage D – Debonding.

Rupture (FRPr) occurs when the FRP material stress reaches its ultimate FRP stress. This failure occurred in the research works of [80] and [3]. End plate plastic hinge failure (P^{end}) occurs when the FRP laminate is short. As the tension steel in the beam midspan reaches its yield stress and begins to rotate, the steel yielding progresses towards the unstrengthened beam and a crack is formed at the end of the FRP laminate; this is then followed by flexural-shear failure. This failure can be observed in [81] and [82]. The failure modes designated by *Cc* start to occur from below the tension steel and are characterised by a more abrupt failure. At the beam midspan, concrete cover debonding, Cc_1^{mid} or concrete cover splitting, Cc_2^{mid} can occur; this happened with [83] and [50], respectively. The beam can also fail by FRP debonding induced by intermediate shear crack, Cc_3^{sp} as in [84]. The beam can also fail at the end of the FRP laminate by concrete cover splitting, Cc_4^{end} or concrete cover debonding, Cc_5^{end} as observed in [76].

4.2.1.4. Beam strengthening. Table 3 presents a summary of the strengthening effects of bio-based FRP on RC beams gotten from the literature considered in this study. The components and mechanical properties of the bio-based FRP, configuration type, concrete grade and beam size, the strengthening effect and resulting failure mode are presented. The failure mode in the table corresponds to the failure modes presented in Fig. 12. It can be observed from the table that the strengthening effect of the bio-based FRP increased with the thickness/ number of layers of the laminate to the extent to which debonding does not occur. It was observed that the FRP-beam configuration also affects the strengthening effects.

For bio-based FRP to be compared with existing commercial FRP materials like CFRP and glass fibre reinforced polymer (GFRP), the material has to be considerably thicker to match their strength. Developed bio-based FRPs by some researchers were able to perform similar to CFRP composites in strengthening RC beams [84–90]. Also, for these bio-based FRPs to be used in the field, durability issues must be adequately addressed.

4.2.2. Concrete columns strengthened with bio-based FRP

Many researchers have explored the confinement of concrete columns with bio-based FRPs. Table 4 overviews the effect of concrete column samples strengthened with bio-based FRP materials. f'_{cc}/f'_{co} is the strengthening ratio that reflects the strengthening effect of the confined concrete, and $\varepsilon_{cc}/\varepsilon_{co}$ is the strain ratio that reflects the stain change due to strengthening material. It can be observed that the strengthening effect of the bio-based FRP material increases with the number of FRP layers. It was also observed that the specimen shape affects the confinement effectiveness; circular columns have a greater strengthening ratio than square columns; the strengthening ratio of square confined columns also increases with the roundness of their edges. Dynamic tests performed by [103,104] were not reported in Table 4.

Precured FRP tubes are a strengthening system developed to replace steel rebars in columns [105]. They were also developed to enhance the compression behaviour of columns exposed to aggressive and corrosive environments, i.e. marine piles; the FRP tubes serve as a lightweight permanent formwork for the column and a non-corrosive reinforcement [106]. Precast bio-based FRP tubes have also been developed in various studies [54,55,107–114]. Since columns are not typically constructed in isolation but have other structural members built into them, precast FRP tubes cannot be used to enhance existing structures but are incorporated in the initial column construction. It has been found that there is no major difference in the behaviour of precast FRP tube confined concrete columns and FRP wrapped concrete columns [115].

4.3. Material design and predictive models

Researchers have predicted the behaviour of bio-based FRP systems

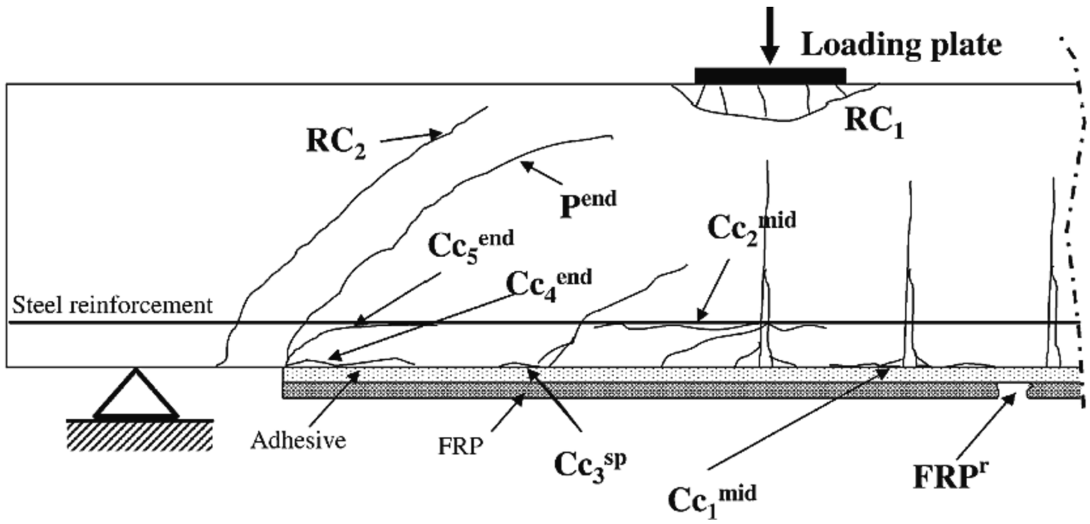

Fig. 12. Failure modes of FRP strengthened RC beam [79].

in various ways. Some authors predicted the behaviour of RC strengthened beam numerical modelling with software like ABACUS [3,86], ANSYS [6,76] and ATENA [70,91], while some have used artificial neural network modelling [74,95]. Some authors have also adopted analytical methods. The *ACI* 440.2R report provides design guidelines for FRP strengthening systems for concrete structures. Following the *ACI* guidelines, Hafizah et al. [80] predicted the moment capacities of beams strengthened with kenaf FRP laminates, and there was a good correlation with the experimental results. Huang et al. [99] also predicted the ultimate loads of flax FRP flexural strengthened RC beams based on the *ACI* guidelines. They found that the analytical results were relatively conservative to the experimental results, with marginal differences from 3% to 40%. Using strain compatibility and force equilibrium equations guided by the BS 8110–1 code, Sayed et al. [66] predicted the first crack load, ultimate load and deflection of a jufe FRP strengthened beam in flexure. The predicted values were also less than the experimental results. Likewise, Jirawattanasomkul et al. [65] evaluated the shear strength of jute FRP strengthened pre-damaged deep beams guided by the JSCE design code [134]. Wang and Xian [69] also predicted the shear strength of flax FRP strengthened RC beams guided by the GB 50367–2013 design code [135]. Chen et al. [85] predicted the flexural capacity of a jute and flax FRP strengthened RC beam using *ACI* [77], JSCE [134], CSA [136] and FIB [137] design codes. The CSA code predicted the RC beams behaviour best, while the *ACI* code gave the most consistent results. In most of the studies reviewed, it was observed that the aim was to detect the extent to which a bio-based material could strengthen a structural member with an arbitrary selection of the number of layers/ thickness of the bio-based FRP. Hardly did the authors follow design guidelines to determine the geometry of the bio-based FRP systems. Nwankwo and Ede [76] designed an kenaf FRP strengthened RC beam to prevent failure by FRP rupture as guided by [138]; they did not consider the possibility of debonding failure and their strengthened beam failed by concrete cover delamination. Alam et al. [92] developed a design guideline for designing NFRP strengthened RC beams in shear and designed an experiment to validate this model.

It is imperative to predict the behaviour of confined columns to enhance engineering design [126]. Various researchers, based on experiments, have developed analytical models to predict the ultimate compressive strength and axial strain of bio-based FRP confined concrete columns. Table 5 presents predictive models for strengthening and strain ratio of concrete columns strengthened with various bio-based FRP composites.

4.4. Durability consideration

The durability of FRP strengthening systems considers the influence of moisture (water, salt and chemical solutions), alkaline environment, fatigue, creep, ultraviolet (UV) radiation, extreme temperature and thermal cycling [139]. Due to the various composite forms, fabrication methods used and expected composite use, the durability performance of FRP composites is somewhat inconsistent [140]. Nambiyanna et al. [59] investigated the water absorption, and fire flow of jute and coir FPR composites used to strengthen RC slabs. Yan et al. [51] evaluated the fire performance of their developed flax FRP composite using a limited oxygen test and found that the developed NFRP composite had a better fire performance than a GFRP composite. Sen and Reddy [97] developed a jute FRP composite to strengthen RC beams. In their study in [140], they evaluated the durability of the composite in terms of normal water and thermal ageing and fire flow study, and evaluated the effects of various chemical and heat treatment on the strength of the composite. Yan and Chouw [141] evaluated the effects of ageing of jute FRP composites in water, seawater and alkaline solution on the mechanical performance of the composites. After exposing NFRP specimens to different environments for 365 days, they found that the composites degraded during that time, and there were changes to the physical and mechanical properties of the composites. Natural fibres have hydroxide functional groups, which make them absorb moisture from its surrounding, weakening the fibre–matrix bond [33]. Several fibre treatments have been used to modify this fibre property. Alkaline [71,76,81,82,92–94] and heat [6,89,96,97] were the predominant fibre pre-treatment used. Alam and Riyami [92] pre-treated jute and kenaf fibres with heat NaOH, and though the treatment reduced the water absorption [142] of the developed NFRP laminates, the strengthening effect of the treated NFRP laminates on RC beams was less than the untreated ones. In the study by Jirawattanasomkul et al. [126], the confinement of concrete columns with jute FRP composite was enhanced with heat-treated fibres. Wroblewski et al. [143] evaluated the effects of heat, freeze/thaw cycles and heat on flax FRP specimens guided by the accelerated condition protocol in *ACI* 440.4R-15 [139]. They found that concrete beams strengthened with NFRP composites left continually in a dry condition at 20 °C had a slightly reduced ultimate load after 63 days, while those exposed continuously to higher temperatures (60 °C) had higher strength after 63 days. This higher strength was due to the FRP's post-curing that increased the polymer matrix cross-link density at that temperature. Similar results were observed in [140].

Table 4
Strengthening effect of concrete columns strengthened with Bio-based FRP material.

S/N	Bio-based FRP Material Components: Fibre type	Fibre form	Polymer	Col. Parameters: Specimen size[a] (mm)	Comp. strength (MPa)	Bio-Based FRP Material Properties: Tensile strength (MPa)	Young's Modulus (GPa)	Strain (%)	No of layers	$\frac{f'_{cc}}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}}$	Ref.
1.	Sisal	Unidirectional strings sewed into sheets	Epoxy	150 × 300	27.02	65	4	1.7	2	1.65	11.70	[57]
									4	2.28	13.17	
	Jute					79.43	13.79	5.65	2	1.92	6.32	
									4	3.15	21.18	
2.	Sisal	Unidirectional braided fibres into sheets	Epoxy	100 × 200	18.10	104	3.19	0.6	3	2.17	4.67	[116]
									6	3.06	6.33	
									9	4.00	8.44	
					38.35				3	1.40	2.60	
									6	1.77	4.30	
									9	2.34	5.40	
									12	3.11	8.10	
				100 × 100 × 200	22.00				3	1.91	5.41	
									6	2.50	6.29	
				Rc = 20					9	3.36	8.35	
					39.20				3	1.18	2.27	
									6	1.62	4.09	
									9	2.05	5.68	
									12	2.44	6.36	
3.	Hemp	Fibre ropes	Epoxy	100 × 300	16.59	177.5	8.6	2.4	1	1.68	7.14	[117]
									2	2.59	10.36	
									3	3.43	13.21	
									4	4.11	15.00	
	cotton					129.3	4.5	13.3	1	0.97	42.86	
									2	2.03	57.14	
									3	2.94	71.0.43	
									4	4.11	77.14	
4.	Hemp	Bidirectional fabrics	Epoxy	200 × 400	18.91				1	1.09		[118]
									2	1.13		
									4	1.22		
5.	Jute	Bidirectional fabric (365 g/m^2)	Epoxy	150 × 300	28.12	23.62	0.638		1	1.23	1.10	[49]
			Polyester			20.56	0.538		1	1.15	1.30	
6.	Flax	Bidirectional fabric	Epoxy – LY 556	150 × 300	42.23				1	1.26		[119]
									2	1.58		
	Hemp	Bidirectional fabric		150 × 300					1	1.14		
									2	1.38		
7.	Flax	Unidirectional fabric	Bio - sourced resin	150 × 300	43.20	216.29	27.00	1.00	2	1.31	3.20	[43]
8.	Jute - Polyester	Bidirectional fabric	Epoxy	150 × 300	13.17	≈ 90.00		≈ 3.2	5	1.47	4.00	[120]
									10	2.27	8.53	
									15	2.61	8.97	
					30.00				5	1.24	1.86	
									10	1.35	2.32	
									15	1.58	2.55	
				150 × 150 × 300	18.42				5	1.34	3.33	
									10	1.79	4.33	
				R_c = 26					15	2.14	4.50	
					29.23				5	1.18	1.38	
									10	1.31	2.00	
									15	1.41	2.17	
9.	Banana	Bidirectional fabric	Epoxy – LY 556	100 × 100 × 600	18.00				1	1.00	2.00	[121]
									2	1.14	2.33	
10.	Sisal	Unidirectional braided fibres into fabrics	Epoxy	100 × 200	22.01	104 ± 0.03	3.19 ± 0.04	3.48 ± 0.02	1	1.84	2.74	[50]
									2	2.72	3.17	
					40.75				1	1.42	2.26	
									2	1.82	3.12	
					58.58				1	1.22	1.67	
									2	1.29	2.43	
		Unidirectional braided fibres into fabrics	Polyester	100 × 200	22.01	80 ± 0.02	3.02 ± 0.01	3.65 ± 0.04	1	1.72	4.02	
									2	2.26	5.57	
					40.75				1	1.27	2.62	
									2	1.50	3.03	
					58.58				1	1.14	1.52	
									2	1.18	1.98	
11.	Sisal	Bidirectional fabric	Epoxy	100 × 200	21.1	177.1	8.59	1.37	1	1.31	4.22	[122]
			Araldite			196.8	8.64	1.84	2	1.57	5.63	
			LY 556			218.7	8.78	2.17	3	1.86	6.59	
12.	Water hyacinth	Bidirectional fabric	Epoxy	100 × 200	7.69	137 ± 5.8	1st stage 15.7 ± 0.06	1.72 ± 0.11	1	1.65		[123]
									2	1.81		
									3	1.98		
							2nd stage		4	2.24		
					33.10		7.19 ± 0.46		1	1.08		

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Table 4 (*continued*)

S/N	Bio-based FRP Material Components Fibre type	 Fibre form	 Polymer	Col. Parameters Specimen size[a] (mm)	 Comp. strength (MPa)	Bio-Based FRP Material Properties Tensile strength (MPa)	 Young's Modulus (GPa)	 Strain (%)	No of layers	$\frac{f'_{cc}}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}}$	Ref.
									2	1.06		
									3	1.09		
									4	1.07		
13.	Flax	Unidirectional fibres ($325 g/m^2$)	Epoxy	150 × 300	10.9	116.65	13.00	1.12	2	1.34	5.02	[124]
									3	1.74	5.86	
									4	1.89	7.65	
14.	Flax (54 % vfc)	Bidirectional fibres ($550 g/m^2$)	Epoxy – Ampreg 22	100 × 200	25.7	102	8.0	3.6	2	1.47	8.53	[107]
						125	9.2	4.4	4	1.95	10.92	
15.	Flax	Bidirectional fibres ($550 g/m^2$; 39 % vfc) – warp	Epoxy	150 × 300	19.06	185	13.6	4.06	4	1.48	9.00	[108]
									8	1.97	12.00	
									12	2.52	12.00	
		Bidirectional fibres (39 % vfc) – weft direction				349.45	19.7	2.35	4	1.76	6.50	
									8	2.23	6.00	
16.	Jute	Bidirectional fabric	Epoxy	100 × 200	20.06	174 ± 18	1st stage 16.35 ± 0.764	1.27	1	1.04	1.09	[125]
									2	1.11	1.60	
									3	1.13	1.34	
							2nd stage 11.834 ± 0.855		4	1.16	3.17	
									5	1.25	7.54	
									6	1.43	9.17	
	Hemp	Bidirectional fabric			21.5	179 ± 7	1st stage 11.631 ± 0.322	2.55	1	1.03	1.11	
									2	1.14	1.54	
									3	1.16	0.83	
							2nd stage 3.69 ± 0.202		4	1.17	1.51	
									5	1.18	1.34	
									6	1.26	1.74	
	Cotton	Bidirectional fabric			18.63	104 ± 2	1st stage 6.446 ± 0.365	3.97	1	1.03	1.69	
									2	1.04	0.91	
									3	1.05	1.49	
							2nd stage 1.339 ± 0.13		4	1.09	0.54	
									5	1.1	1.14	
									6	1.22	10.74	
17.	Jute	Bidirectional fabric	Epoxy	100 × 200	28.3	203	14.485	2.2	1	1.21		[126]
18.	Hemp	Fibre ropes	Epoxy	150 × 150 × 300 $R_c = 0$	16.1	177.4		2.3	1	1.37	4.44	[127]
									2	1.70	6.14	
									3	2.05	7.09	
				150 × 150 × 300 $R_c = 13$	15.4				1	1.56	5.58	
									2	2.05	7.68	
									3	2.47	9.53	
				150 × 150 × 300 $R_c = 26$	14.9				1	1.74	5.82	
									2	2.32	8.20	
									3	2.82	10.47	
	cotton	Fibre ropes	Epoxy	150 × 150 × 300 $R_c = 0$	16.1	129.2		13.2	1	0.57	14.10	
									2	1.11	22.50	
									3	1.52	30.00	
				150 × 150 × 300 $R_c = 13$	15.4				1	0.78	20.07	
									2	1.33	31.41	
									3	1.87	42.12	
				150 × 150 × 300 $R_c = 26$	14.9				1	0.97	24.43	
									2	1.61	40.14	
									3	2.35	55.84	
19.	Flax	Bidirectional fabric ($550 g/m^2$)	Epoxy – Ampreg 22 resin	100 × 200	21.2	112	8.9	3.3	2	1.30	4.73	[52]
						134	9.6	3.9	4	1.78	6.32	
						142	10.4	4.4	6	2.34	7.90	
20.	**Kenaf**	Fibre	Polyester	500-height					3	≈ 1.15		[128]
21.	Flax	Bidirectional fabric	Epoxy – SP prime 20LV		39.16				1	1.12	7.59	[109]
22.	Flax	Bidirectional fabric ($360 g/m^2$)	Epoxy	150 × 300	27.54	85.1	3.68	2.59	3	0.91	3.38	[110]
						81.3	3.22	2.94	6	111	5.88	
						69.3	2.66	3.16	9	1.42	6.29	
				150 × 300	32.84	85.1	3.68	2.59	3	0.71	3.44	
						81.3	3.22	2.94	6	1.00	4.85	
						69.3	2.66	3.16	9	1.43	4.98	
23.	Flax (55 % vfc)	Bidirectional fabric ($360 g/m^2$)	Epoxy – Ampreg 22	100 × 200	31.2	134	9.5	4.3	4	1.99	12.00	[111]
24.	Flax	Bidirectional fabric ($550 g/m^2$; 55 % vfc)	Epoxy	100 × 200	25.8	106	8.7	3.7	2	1.43	8.60	[112]
						134	9.5	4.3	4	2.08	11.25	
25.	Jute	Bidirectional fabric	Epoxy – Sikadur 330			45.2	4.264	1.06		1.13		[129]
26.	Flax	Bidirectional fabric ($550 g/m^2$; 55 % vfc)	Epoxy – Prime LV 20	100 × 200	21.5	128.1 ± 8.0	9.4 ± 1.0	3.1 ± 0.2	2	1.59	3.68	[54]
									4	2.35	5.09	
									6	3.14	6.41	
27.				100 × 200	25.8	106	8.7	3.7	2	1.43	8.60	[55]

(*continued on next page*)

Table 4 (*continued*)

S/N	Bio-based FRP Material Components			Col. Parameters		Bio-Based FRP Material Properties				$\frac{f'_{cc}}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}}$	Ref.
	Fibre type	Fibre form	Polymer	Specimen size[a] (mm)	Comp. strength (MPa)	Tensile strength (MPa)	Young's Modulus (GPa)	Strain (%)	No of layers			
	Flax	Bidirectional fibres (550 g/m^2; 54 % vfc)	Epoxy – Ampreg 22			134	9.5	4.3	4	2.08	11.25	
28.	Flax	Bidirectional fabric (240 g/m^2; 54 % vfc)	Epoxy	100 × 200	32.25				8	2.05	3.65	[130]
29.	Jute	Bidirectional fabric	Epoxy – Sikadur 330	100 × 200	30.32	36	3.46	1.04	1	1.17		[131]
30.	Jute	Bidirectional fabric	Epoxy – Sikadur 330	100 × 200	21.55	45.2	4.26	1.06	2 3	1.37 1.57		[132]
31.	Jute Sisal	Bidirectional fabric	Epoxy – MBrace	103 × 200	20	189.48 223.34	32.5 42.5		1 1	1.49 1.66		[133]
32.	Flax	Unidirectional fabric	Bio Epoxy CHS520/ Cardolite NX 5619	150 × 300	43	216.29	27	1.00	2	1.23	≈ 1.89	[44]
33.	Bamboo	Twining sheet	Epoxy – L500-AS/L-500BS	150 × 300	26.51	81.94			5 10 15	1.12 1.37 1.67	2.56 3.34 4.27	[113]

[a] Specimen size – diameter × height (cylinder specimen) or length × breath × height (cube specimen).

Table 5
Strength and strain models for bio-based FRP confined columns.

S/N	Fibre Type	Fibre form	Specimen shape	Strengthening ratio f'_{cc}/f'_{co}	Strain ratio $\varepsilon_{cc}/\varepsilon_{co}$	Ref.
1.	Sisal	Unidirectional braided fibres into sheets	Cylinder	$\frac{f'_{cc}}{f'_{co}} = 1 + 3.0\frac{f_1}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + 6.7\frac{f_1}{f'_{co}}$	[116]
2.	Sisal	Unidirectional braided fibres into sheets	Cube	$\frac{f'_{cc}}{f'_{co}} = 1 + 2.5\frac{f_1}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + 7.0\frac{f_1}{f'_{co}}$	[116]
3.	Sisal	Bidirectional fabric	Cylinder	$\frac{f'_{cc}}{f'_{co}} = 1 + 1.06\frac{f_1}{f'_{co}}$		[122]
4.	Flax	Bidirectional fabric	Cylinder		$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 0.46 + 6.21\left(\frac{f'_{cc}}{f'_{co}}\right)^{0.7}$	[107]
5.	Flax	Bidirectional fabric	Cylinder	$\frac{f'_{cc}}{f'_{co}} = 1 + 1.82\frac{f_1}{f'_{co}}$		[52]
6.	Flax	Bidirectional fabric	Cylinder	$\frac{f'_{cc}}{f'_{co}} = 1 + 1.95\frac{f_1}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + 12.44\left(\frac{f_1}{f'_{co}}\right)^{0.756}$	[110]
7.	Hemp	Fibre ropes	Cylinder	$\frac{f'_{cc}}{f'_{co}} = 1 + 2.7\frac{f_1}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + 10\frac{f_1}{f'_{co}}$	[117]
8.	Hemp	Fibre ropes	Cube	$\frac{f'_{cc}}{f'_{co}} = 1 + 2.7k_s^{0.90}\frac{f_1}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + 10k_s^{1.10}\frac{f_1}{f'_{co}}$	[127]
9.	Cotton	Fibre ropes	Cylinder	$\frac{f'_{cc}}{f'_{co}} = 1 + 2.7\frac{f_1}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 26 + 53\frac{f_1}{f'_{co}}$	[117]
10.	Cotton	Fibre ropes	Cube	$\frac{f'_{cc}}{f'_{co}} = 1 + 2.7k_s^{1.72}\frac{f_1}{f'_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 26 + 53k_s^{2.20}\frac{f_1}{f'_{co}}$	[127]
11.	Jute Hemp Cotton	Bidirectional fabric	Cylinder	$\frac{f'_{cc}}{f'_{co}} = 1 + 7.68\frac{f_1^{0.74}}{f'_{co}}$		[125]
12.	Jute	Heat treated bidirectional fabric	Cylinder	$\frac{f'_{cc}}{f'_{co}} = 1 + 16.9\frac{f_1^{0.23}}{f'_{co}}$		[126]

ε_{cc} = Ultimate strain of confined concrete.
ε_{co} = strain of unconfined concrete.
A_g = gross cross-sectional area = $bh - (4 - \pi)R_c^2$.
b = width of square section.
d = diameter of core concrete in circular section.
f_1 = lateral confining pressure = $2f_{FRP}t/d$.
f'_{cc} = compressive strength of confined concrete.
f'_{co} = compressive strength of unconfined concrete.
f_{FRP} = tensile strength of FRP in the hoop direction.
h = depth of square section.
k_s = shape factor.
$k_s = 1 - [(b - 2R_c)^2 + (h - 2R_c)^2] / 3A_g$.
R_C = corner radius of square section.
t = thickness of FRP.

4.5. Sustainability and cost considerations

It has been suggested that since natural fibres are much cheaper than carbon and glass fibres, replacing synthetic fibres with natural fibres in FRP will produce a more sustainable and cheaper composite [125]. Chen et al. [85] made this conclusion with their developed jute and flax FRP composites but did not account for the epoxy content in the cost analysis. Yoopraserrchai et al. [57] compared the cost of sisal and jute FRP composites with CFRP to strengthen RC columns. They found that though the NFRP composites needed much more epoxy resin than the CFRP sheets, the developed NFRP composites were still cheaper than the CFRP alternative. Contrarily, Jirawattanasomkul et al. [123] found that their developed water hyacinth FRP composite used for concrete column confinement had a higher cost-to-confined compressive strength ratio than CFRP. They also found that the cost-efficiency of their NFRP composite reduced with the increased strength of the RC member to be strengthened. Though the NFPR composite was relatively more expensive than CFRP, it had a better environmental impact than CFPR; the NFRP composite had a less environmental impact in 17 of the 18 categories. Chen et al. [84] compared flax and jute FRP composites with CFRP used to strengthen RC beams and found that the cost-efficiency of the developed NFRP composite varied with the NFRP geometric parameters. RC beams strengthened with NFRP laminates with four layers were more cost-efficient than those strengthened with CFRP. While the RC beams strengthened with six and eight NFRP laminate layers were less cost-efficient than those strengthened with CFRP. The NFRP composites had less environmental impact than CFRP in 6 categories, and the epoxy component had the more significant contribution in 5 of these 6 categories. Li et al. [87] also had similarly mixed results. They compared flax FRP composites with CFRP used to strengthen RC beams and found that the cost-efficiency of the developed NFRP composite varied with the NFRP geometric parameters and fabrication method. NFRP laminates with up to eight layers were less cost-efficient than the CFRP alternative, whereas NFRP laminates with four layers were more cost-efficient than the CFRP alternative. An environmental impact assessment was also done, and the NFRP composite had a lower environmental impact in 9 of the 12 categories considered.

5. Further studies

Some areas for further studies regarding the material development and design of bio-based FRP for strengthening concrete structures are presented below:

i. Design: Effective design models need to be developed for the flexural strengthening of RC beams with bio-based FRP materials. It should consider the effect of beam reinforcement ratio and concrete strength in determining the optimum FRP geometric properties (thickness, width, length) of the FRP system. Possible failure modes should guide developed design formulations, and stress limits should be set to prevent abrupt debonding failure.

Developed column confinement predictive models should be tested on full-scale reinforced concrete columns since FRP confinement effectiveness is a function of the stiffness of the column member to be strengthened. The effectiveness of predictive models concerning fibre type, form and FRP strength should be evaluated.

ii. Durability: The durability of bio-based FRP composites used to strengthen full-scale structural elements in different exposure conditions should be studies. FRP surface protective measures should also be developed.

iii. Sustainable material: Further studies on the FRP composites with biopolymers need to be done, and the environmental impact of the bio-based FRP strengthening system during its service life and at the disposal phase should be assessed.

iv. Fabrication method: FRP fabrication techniques need to be advanced further to minimize the variability of the developed composite and limit voids within the material. Also, larger fibre contents are difficult to attain while making precured laminates with the hand lay-up method; more studies should be done to develop other fabrication methods like vacuum infusion.

v. Loading protocols: In evaluating the effectiveness for bio-based FRP strengthening systems, there has been a focus on monotonic loading conditions. It is also important to understand how strengthened concrete members respond under the action of variable loads and in the event of seismic loading. Fatigue effects should also be assessed.

6. Conclusion

A mixed-method of bibliometric and systematic literature review was done to converge the current ideas in developing bio-based FRP for strengthening concrete structures. A total of 87 documents retrieved from SCOPUS and Google scholar based on specified search parameters were considered for this study. From the bibliometric analysis, the trend of research output in this area was analysed, and the leading countries, authors and keywords were identified. It was found that this area is still developing, with the first identified research output in the area published in 2012. The following conclusions were drawn from the literature review:

i. RC beams and concrete columns are the elements that have been considered the most by researchers in the study area.
ii. Flax and jute fibres are the leading fibres in developing bio-based FRPs for strengthening concrete structures, and epoxy is the most used polymer.
iii. When bio-based FRPs are used to strengthen RC beams, various FRP configurations have been considered, and shear or flexural strengthening is predominately done. The FRP strengthening effect increases with the thickness of the developed laminate, but up to a certain extent beyond which debonding occurs. FRP anchorage can be used to prevent premature FRP debonding. The various beam failure modes that occur with synthetic FRP systems also exist with NFRP systems.
iv. When bio-based FRPs are used to strengthen concrete columns, the strengthening effect is directly related to the thickness of the FRP material. The confinement effectiveness increases with the thickness of the FRP material.
v. For concrete members strengthened with bio-based FRP, the effectiveness of the FRP depends on the stiffness of the member to be strengthened.
vi. The behaviour of concrete members strengthened with bio-based FRP can be effectively modelled with analytical and numerical methods.
vii. Bio-based FRP can degrade or be enhanced in certain environments. Natural fibre properties can be modified with heat and alkaline treatments.
viii. The synthetic polymer content must be controlled for NFRP composites to be cheaper than synthetic FRPs. The synthetic polymer component of NFRP, in many cases, invalidates the sustainability advantages of using natural fibres. For NFRP composites to indeed be a sustainable material, bio-based polymer needs to replace the synthetic polymer.
ix. Though several researchers have conducted experiments to understand the behaviour of RC beams strengthened with bio-based FRP, more theoretical formulations should be carried out to develop accurate predictive models.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This research is funded by the Intra-Africa Mobility Scheme of the

European Union in partnership with the African Union under the Africa Sustainable Infrastructure Mobility (ASIM) scheme. Opinions and conclusions are those of the authors and are not necessarily attributable to ASIM. The work is supported and part of collaborative research at the Centre of Applied Research and Innovation in the Built Environment (CARINBE).

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