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Exploration of Cellulose-Based Matrix Materials: A Comparative Study in the Development of Radar Absorbing Materials for Military Applications

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Abstract
Exploring cellulose-based matrix materials for Radar Absorbing Materials (RAM) is a strategic way to advance defence technology, emphasising both technical effectiveness and environmental sustainability. This study uses a systematic literature review (SLR) approach to identify, evaluate and analyse previous research on the use of cellulose-based matrices compared with conventional materials such as epoxy, polyurethane (PU) and graphene. Comprehensive data was collected from indexed scientific databases (ScienceDirect, SpringerLink, Wiley and Google Scholar), covering publications from 2013 to 2025. The findings reveal that, when combined with graphene or carbon nanotube (CNT) fillers, cellulose aerogels can achieve reflection loss (RL) values as low as −70 dB, outperforming most conventional materials. Furthermore, carboxymethyl cellulose (CMC) with an ultrathin thickness of only 0.028 mm demonstrates high absorption efficiency of 98.2%. While limitations remain in terms of bandwidth and thermal stability, cellulose offers significant advantages, including low density, low cost, biodegradability and the availability of renewable resources. These results highlight cellulose as a highly promising alternative matrix material for RAM in military applications, while simultaneously supporting the green defence agenda and strengthening the resilience of the defence industry.
Keywords: *cellulose matrix, radar absorbing material (ram), military stealth, bandwidth performance, biomass-based materials*

Abstrak
Eksplorasi material matriks berbasis selulosa untuk Radar Absorbing Material (RAM) menghadirkan peluang strategis dalam pengembangan teknologi pertahanan yang menekankan tidak hanya efektivitas teknis, tetapi juga keberlanjutan lingkungan. Penelitian ini menggunakan pendekatan Systematic Literature Review (SLR) untuk mengidentifikasi, mengevaluasi, dan menganalisis berbagai penelitian terdahulu yang berkaitan dengan penerapan matriks berbasis selulosa dibandingkan dengan material konvensional seperti epoksi, poliuretan (PU), dan grafena. Proses tinjauan dilakukan melalui pengumpulan data secara komprehensif dari basis data ilmiah terindeks (ScienceDirect, SpringerLink, Wiley, dan Google Scholar) yang mencakup publikasi dari tahun 2013 hingga 2025. Hasil kajian menunjukkan bahwa aerogel selulosa yang dikombinasikan dengan pengisi grafena atau CNT dapat mencapai nilai Reflection Loss (RL) serendah −70 dB, melampaui sebagian besar material konvensional. Selain itu, Carboxymethyl Cellulose (CMC) dengan ketebalan ultratipis hanya 0,028 mm menunjukkan efisiensi penyerapan tinggi hingga 98,2%. Meskipun masih terdapat keterbatasan dalam hal bandwidth dan stabilitas termal, selulosa menawarkan keunggulan signifikan seperti densitas rendah, biaya murah, sifat biodegradable, dan ketersediaan sumber daya terbarukan. Hasil penelitian ini menegaskan bahwa selulosa merupakan material matriks alternatif yang sangat menjanjikan untuk aplikasi RAM di bidang militer, sekaligus mendukung agenda pertahanan hijau dan memperkuat ketahanan industri pertahanan.
Kata Kunci: *matrix selulosa, radar absorbing material (ram), siluman militer, kinerja bandwidth, material berbasis biomassa*

1. Introduction

Radar Absorbing Materials (RAM) are specialized composites engineered to minimize the reflection of electromagnetic (EM) waves, thereby enhancing stealth capabilities primarily in military applications by reducing the radar cross-section (RCS) [1]. Typically consisting of a polymer matrix filled with lossy dielectric or magnetic fillers like ferrites, their absorption performance is tailored by manipulating microstructure, composition, and geometry. Research continues to enhance these materials, incorporating nanoparticles such as iron oxide (Fe_3O_4) to improve magnetic characteristics and microwave absorption, and leveraging nanotechnology and hybrid structures in composites like ferrite/epoxy [2]. Beyond military use, RAM applications are expanding into civil engineering, telecommunications, and electromagnetic interference (EMI) shielding. Current research focuses on innovative approaches, including nature-inspired bionic designs, advanced manufacturing like 3D printing, and integration with plasma technology, driven by the need for multifunctional materials in complex detection environments and advancing radar systems [3].

Cellulose has garnered increasing attention as an alternative material due to its biodegradable, abundant, and environmentally friendly properties. It has been widely utilized across various industrial sectors. In the field of materials, cellulose from empty fruit bunches of oil palm has proven to be a potential material for eco-friendly bioplastics [4], while its combination with sago starch produces alternative packaging materials as a substitute for styrofoam [5]. In the energy sector, cellulose waste from the paper industry can be converted into bioethanol through hydrolysis and fermentation processes, while also contributing to the reduction of industrial waste [6].

The application of cellulose is also evident in the food industry, such as its use as an edible coating to reduce oil absorption [7], and the formation of cellulose particles to improve product consistency and texture [8]. In energy storage technology, cellulose is used in the fabrication of robust and sustainable battery separators [9]. This diversity of applications underscores the significant potential of cellulose as a multifunctional material relevant for the development of future technologies.

Based on this potential, cellulose presents a significant opportunity to be developed as a matrix material for RAM, offering not only technical effectiveness but also environmental sustainability. Therefore, this study aims to conduct a comparative literature review of various RAM matrix materials, with a specific focus on cellulose-based materials, to evaluate their potential and performance for military applications.

2. Material and Method

This study employs the Systematic Literature Review (SLR) method to identify, evaluate, and analyze findings from previous research relevant to the use of matrix materials in Radar Absorbing Materials (RAM), with specific focus on cellulose-based materials for military applications. The SLR method was selected because it enables researchers to gain a comprehensive and structures understanding of the developments, trends, and research gaps within this topic. The SLR process was conducted through several key stages, as follows:

Formulation of Research Questions

The primary research question of this study is: *"What is the potential and performance of cellulose-based matrix materials compared to other conventional materials in Radar Absorbing Material (RAM) for military applications?"*

Literature Search Strategy

The literature search was performed on scientific databases, including ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. The search utilized the following keywords: *"radar absorbing material"*, *"matrix material"*, *"cellulose composite"*, *"military stealth technology"*, and *"comparative study"*. The publication year range was focused on the period from 2013 to 2025 to capture the most recent advancements.

Inclusion and Exclusion Criteria

Articles included in the review met the following criteria:

- Published in indexed, peer-reviewed scientific journals.
- Discuss matrix materials in RAM, particularly cellulose-based materials of comparator materials such as epoxy, synthetic polymers, and hybrid composites.
- Present relevant data or analysis on material performance, such as dielectric constant, wave absorption effectiveness, density, thermal stability, or environmental sustainability.

Articles that did not provide relevant technical data or did not directly address RAM material aspects were excluded from the study.

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Selection and Data Extraction

From the initial search results, a total of 50 articles were identified. After a filtering process based on title, abstract, and full-text assessment against the inclusion criteria 25 articles remained for in-depth analysis. 39 articles remained for title and 31 articles for abstract screening. Of these, 14 were excluded due to irrelevance, leaving 25 full-text articles for eligibility assessment. Finally, 15 articles were included in the review. Data from the selected articles were extracted and categorized based on the type of matrix material, synthesis or fabrication methods, and the reported performance parameters.

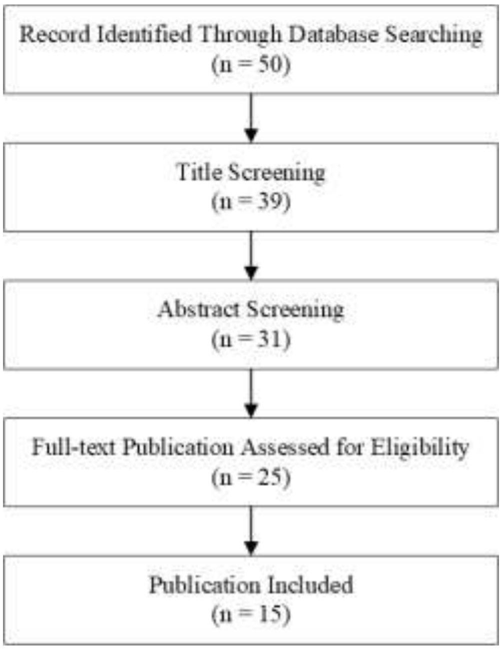

Figure 1. Prisma 2020 Diagram

Data Analysis and Synthesis

The extracted data were analyzed comparatively to identify the advantages and limitations of each matrix material. The analysis focused on the potential of cellulose as an alternative materials that offers not only technical effectiveness but also supports environmental sustainability in the development of RAM for military applications.

3. Results and Discussion

Based on the literature review conducted, various matrix materials have been identified as potential candidates for application as Radar Absorbing Materials (RAM). The performance of these materials is validated through key parameters, namely minimum Reflection Loss (RL), absorption bandwidth, and material thickness. The collected data reveal that cellulose-based materials, such as cellulose aerogel and carboxymethyl cellulose (CMC), exhibit highly competitive capabilities.

Table 1. Electromagnetic Wave Absorbing Materials

Matrix Material	Filler/Composite	RL Minimum (dB)	Bandwidth RL ≤ -10 dB (GHz)	Source
Magnetite (Fe_3O_4)	Micro-nano particles	-35.36 dB @10 GHz	3.63 GHz	Elmahaishi et al., 2024 [10]
Cellulose aerogel	Graphene/CNT	-70 dB	9 GHz	Song et al., 2025 [11]
CMC (Carboxymethyl cellulose)	MWCNT@Fe_3O_4	Reflection 0.23 dB (98.2%)	-	Dai et al., 2024 [12]
Carbon aerogel (kapok fiber)	Fe_3O_4 + lauric acid	-17.3 dB	-	Song et al., 2021 [13]
Epoxy resin	0.5 wt% MWCNT + NaDDBS	-26.1 dB @ 11.2 GHz	8.8-11.4 GHz	Che et al., 2014 [14]
Polyacrylonitrile fiber	RGO-Ni core-shell composite	-54.16 dB	9.71 GHz	Wang et al., 2023 [15]

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Matrix Material	Filler/Composite	RL Minimum (dB)	Bandwidth RL ≤ -10 dB (GHz)	Source
Rgo	Fe_3O_4@RGO core-shell composite	-55.71 dB @ 6.78 GHz		Yu et al., 2023 [16]
Graphene	Graphene aerogel microspheres	-52.7 dB	9.3 GHz	Li et al., 2020 [17]
Composite aerogel	LFO/N-RGO composite aerogel	-64.5 dB	6.72 GHz	Fu et al., 2023 [18]
Epoxy resin	N-doped RGO/CeO_2 nanocomposites	-57.2 dB	4.6 GHz	Li et al., 2021
Polypropylene	RGO/PP 3D absorber	RL ≤-10 dB (full band)	2-40 GHz, 75-110 GHz	Zhang et al., 2019 [19]
Carbonated foam	RGO + $Co_{1.29}Ni_{1.71}O_4$ composite foam	-53.45 dB	7.45 GHz	Shi et al., 2024 [20]
rGO (as matrix)	Fe_3O_4/ZnO/PANI/rGO (50% rGO)	-8.57 dB @ 11.10 GHz	-	Hanifah et al., 2024 [21]
Plexiglas	PANi-Graphene (graded conductivity)	≈ -10 dB	7.8-14.0 GHz	Thomas et al., 2020 [22]
Polyurethane (PU) foam	Fe_3O_4/Graphene	-58.5 dB 10.9 GHz	3.0-16.8 GHz (13.8 GHz)	Zhang et al., 2021 [23]

Summary of Findings and In-Depth Performance Analysis of Materials

A comparative analysis of data from various scientific publications reveals a wide spectrum of material performance. At the peak of absorption performance, cellulose aerogel integrated with graphene or CNT fillers recorded an outstanding Reflection Loss (RL) value of −70 dB (Song et al., 2022). This value not only demonstrates exceptional electromagnetic energy absorption capability (with only 0.00001% of incident waves reflected) but also places this material among the top-performing RAMs examined. Such remarkable performance is likely attributed to the nanoporosity of the aerogel structure, which provides extended propagation paths and abundant interfaces for energy dissipation.

In contrast, a different approach is exemplified by Carboxymethyl Cellulose (CMC) combined with MWCNT@Fe_3O_4 composites. This material achieved an absorption efficiency of 98.2% at an extremely thin thickness of only 0.028 mm (Dai et al., 2024). The combination of ultrathin dimensions and high absorption efficiency indicates significant potential for applications on highly constrained surfaces, such as next-generation fighter aircraft coatings or portable electronic devices requiring EMI shielding, without adding substantial weight or volume.

As a primary benchmark, conventional materials such as epoxy resin reinforced with 0.5 wt% MWCNT have been reported to achieve an RL of −26.1 dB at 11.2 GHz with an effective bandwidth (RL ≤ −10 dB) of 2.6 GHz [14]. Although its RL value is lower compared to cellulose aerogel, epoxy remains a preferred option due to its proven thermal and mechanical stability. Meanwhile, polyurethane (PU) foam filled with Fe_3O_4/graphene composites demonstrated a notable advantage in terms of bandwidth, achieving an RL of −58.5 dB at 10.9 GHz and an exceptionally wide effective bandwidth of 13.8 GHz (ranging from 3.0 to 16.8 GHz) at a thickness of 2.5 mm [23]. Such broad bandwidth is particularly valuable for broadband stealth applications that must counter diverse radar systems.

Advanced carbon-based materials such as LFO/N-RGO composite aerogels also exhibited outstanding performance with an RL of −64.5 dB (Fu et al., 2023), underscoring that aerogel-based materials in general—including cellulose-derived ones—offer a highly promising platform for the engineering of high-performance RAMs.

Comprehensive Comparison: Cellulose-Based vs. Conventional Materials

Compared to epoxy, cellulose aerogels not only demonstrate a significant advantage in terms of RL values (−70 dB vs. −26.1 dB), but also offer fundamental benefits regarding environmental footprint. Epoxy resin, being a petroleum-derived material, possesses an unsustainable life cycle—from raw material extraction and energy-intensive production to challenges in end-of-life recycling. In contrast, cellulose is derived from renewable biomass, is biodegradable, and can utilize agricultural waste [4], thereby aligning with the principles of the circular economy. Nevertheless, epoxy still holds superiority in dimensional stability, chemical resistance, and adhesion, which have been extensively validated under extreme operational conditions.

Table 2. Comparison Between Cellulose-Based vs. Conventional Materials

Comparison	Findings	Scientific Notes
Cellulose vs. Epoxy	- Cellulose aerogel with graphene/CNT fillers achieves RL −70 dB, outperforming epoxy with MWCNT (−26.1 dB). - CMC with an ultrathin thickness (0.028 mm) still absorbs 98.2% of radar waves. - Epoxy is more commonly used but has higher density and is less environmentally friendly.	Cellulose demonstrates superior absorption efficiency and sustainability, whereas epoxy remains widely applied due to mechanical and thermal stability.
Cellulose vs. Polyurethane (PU)	- PU foam exhibits very broad bandwidth (13.8 GHz) and RL −58.5 dB, suitable for broadband applications. - Cellulose excels in biodegradability and renewable resource availability.	PU is advantageous for broadband stealth applications, while cellulose is preferable from an environmental perspective.
Cellulose vs. Polyaniline (PANI)/Graphene	- Conductive materials such as rGO and graphene show excellent RL values (up to −64.5 dB) but are expensive and require complex synthesis. - Cellulose provides a low-cost, abundant, and eco-friendly alternative.	While PANI/graphene-based materials offer high performance, cellulose offers scalability and sustainability

In comparison with PU foam, cellulose appears less competitive in terms of effective bandwidth (e.g., 9 GHz for cellulose aerogels versus 13.8 GHz for PU foam). However, cellulose offers lower density, resulting in lighter materials—an attribute of critical importance in the aerospace industry, where weight reduction directly translates into improved fuel efficiency and maneuverability. Furthermore, from a life-cycle perspective, PU foam, as a synthetic polymer, generates hazardous emissions when burned and leaves persistent waste in the environment.

When benchmarked against advanced graphene or reduced Graphene Oxide (rGO) materials, cellulose provides a considerably lower production cost without substantially compromising performance. For instance, cellulose aerogels with an RL of −70 dB (Song et al., 2022) outperform graphene aerogel microspheres, which were reported by Li et al. (2020) to achieve an RL of −52.7 dB [17]. The synthesis of graphene and its derivatives remains complex, energy-intensive, and costly, posing barriers to large-scale production—particularly for military applications that demand high-volume deployment. By contrast, cellulose, as an abundant and inexpensive resource, offers a more economically feasible pathway for the large-scale fabrication of RAMs.

Multi-Aspect Performance Analysis of Materials: Beyond Reflection Loss

Table 3. Comparative Multi-Aspect Analysis of Cellulose-Based vs. Conventional Materials

Aspect	Cellulose-Based Materials	Epoxy/PU/Graphene-Based Materials
Reflection Loss	Excellent (-70 dB)	Good (-26 to -65 dB)
Bandwidth	Moderate (6-9 GHz)	Wide (up to 13.8 GHz)
Density	Low (lightweight)	Variable, generally higher
Thermal Stability	Limited	High
Cost	Low	High
Sustainability	Excellent	Limited

A comprehensive evaluation necessitates moving beyond Reflection Loss (RL) alone and considering other performance aspects:

a. Reflection Loss (RL) and Absorption Mechanism
   The superior RL performance of cellulose-based materials, particularly in aerogel form, originates from their highly porous structure. This architecture promotes multiple reflections and scattering of electromagnetic waves within the material, effectively converting wave energy into heat. When combined with conductive fillers (e.g., graphene) or magnetic fillers (e.g., Fe_3O_4), a conductive network and synergistic magnetic loss effects are formed, further enhancing the overall absorption mechanisms.

b. Bandwidth
   Bandwidth remains an area for improvement in cellulose-based RAM. Their effective absorption bandwidth typically falls within the moderate range (6–9 GHz), whereas materials such as PU foams can exceed 13 GHz. Bandwidth performance is highly dependent on impedance matching and the dispersive properties of the material. Future strategies to expand the bandwidth of cellulose-based absorbers may include multi-layer structural engineering or the incorporation of hybrid fillers with complementary electromagnetic properties.
c. Density and Weight
   Low density represents a decisive advantage of cellulose-based aerogels, which typically exhibit densities below 100 mg/cm³. This results in exceptionally lightweight materials. In military applications such as unmanned aerial vehicles (UAVs) or satellites, weight reduction is a critical factor that can extend operational duration and increase payload capacity.
d. Thermal Stability
   Thermal stability is a primary limitation of cellulose. Inherently, cellulose begins to degrade at temperatures above 200 °C, whereas epoxy and PU can retain their integrity up to approximately 300°C. To overcome this limitation, strategies such as chemical modification (e.g., crosslinking with heat-resistant agents) or forming composites with functional ceramics can be pursued to expand the high-temperature operational window.
e. Cost and Sustainability
   This represents the most distinctive advantage of cellulose-based materials. Their life cycle—from renewable resource origins and relatively low-energy production processes to biodegradability—renders them superior in the current era emphasizing green technologies. Within the context of national defense policy, the development of cellulose-based RAM sourced from agricultural waste can also enhance supply chain resilience and reduce dependence on imported strategic materials.

Strategic Potential and Technical Challenges in the Development of Cellulose-Based RAM

The strategic potential of cellulose-based materials for military applications is both multidimensional and highly promising. First, the utilization of local and renewable resources such as empty fruit bunches of oil palm [4], kapok fiber [13], or bacterial cellulose creates opportunities for establishing an independent and competitive upstream industry. Second, the hydroxyl functional groups along the cellulose chain provide chemical "handles" for various functional modifications, enabling engineered surface properties to improve filler dispersion and adhesion with metallic substrates. Third, from a policy and strategic communication perspective, the adoption of “green” RAM aligns with global commitments to reduce carbon emissions and promote sustainable defense (green defense), offering additional value in the realm of international diplomacy.

Table 4. Strategic Potential and Technical Challenges

Strategic Potential	Technical Challenges
- Derived from renewable and abundant resources (e.g., agricultural residues, wood, and related biomass). - Biodegradable and environmentally friendly. - Extremely thin layers allow application on limited or constrained surfaces.	- Lower thermal stability compared to synthetic polymers. - Hydrophilic nature, leading to water absorption that affects electromagnetic performance. - Requires chemical modification to improve compatibility with conductive fillers. - Limited field studies for extreme military applications.

Despite its strategic promise, the path toward full operational deployment of cellulose-based RAM is constrained by several technical challenges. The hydrophilic nature of cellulose leads to significant water absorption, which alters its dielectric constant and degrades microwave absorption performance; this necessitates the development of effective hydrophobic coatings or chemical grafting techniques. Moreover, cellulose exhibits limited thermal stability compared to synthetic polymers and must also demonstrate resistance to UV radiation, fluctuating humidity, and exposure to operational chemicals (e.g., lubricants, aviation fuels) through accelerated aging tests and long-term field studies. The transition from laboratory-scale production to industrial-scale manufacturing further requires process optimization—such as supercritical drying for aerogels—to ensure consistency, reproducibility, and sufficient production rates. Finally, the absence of robust computational models to predict the electromagnetic behavior of cellulose composites hampers design efficiency, underscoring the need for accurate simulation tools to reduce reliance on costly trial-and-error development.

4. Conclusion

The exploration of cellulose-based matrix materials for Radar Absorbing Material (RAM) applications in the military field not only demonstrates their technical feasibility but also opens a new paradigm of how advanced defense technologies can be integrated with the principles of environmental sustainability. The accumulated data convincingly indicate that with proper material engineering, particularly through the development of hybrid composites and the optimization of nanoscale structures, cellulose-based materials can not only match but, in some aspects, even surpass the performance of conventional materials. Although challenges remain in terms of environmental stability and the maturation of manufacturing technologies, investment in research and development in this area holds immense potential returns. These are not limited to the creation of more effective and lightweight stealth systems but also extend to laying the foundation for a defense industry that is more self-reliant, resilient, and ecologically responsible, addressing the defense challenges of the 21st century.

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