Tikrit Journal of Engineering Sciences (2023) 30 (1): 104-111
DOI: http://doi.org/10.25130/tjes.30.1.10

IRAQI Academic Scientific Journals

College of Engineering

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Insulation Materials Based on Recycled Feather Waste: A Review

Abdulmunem R. Abdulmunem[a]*, *Pakharuddin M. Samin*[b], *Izhari I. Mazali*[b], *Abdullateef A. Jadallah*[c], *Khalid F. Sultan*[a]

a Electromechanical Engineering Department, University of Technology- Iraq, Baghdad, Iraq.
b School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Johor 81310, Malaysia.
c College of Engineering /Alshirqat-Tikrit university

Keywords:

Feather Waste; Recycled Waste; Sustainable Materials; Thermal Insulation; Acoustic Insulation

ARTICLE INFO

Article history:

Received	10 Nov.	2022
Accepted	17 Mar.	2023
Available online	31 Mar.	2023

Citation: Abdulmunem AR, Samin PM, Mazali II, Jadallah AA, Sultan KF. Insulation Materials Based on Recycled Feather Waste: A Review. Tikrit Journal of Engineering Sciences 2023; 30(1): 104-111.
http://doi.org/10.25130/tjes.30.1.10

***Corresponding author:**

Abdulmunem R. Abdulmunem

Electromechanical Engineering Department,
University of Technology- Iraq, Baghdad, Iraq.

Abstract: Recently, the world has been moving towards reusing wastes in many industrial applications, such as buildings and automotive, to eliminate the environmental pollution impact due to increasing waste worldwide. Besides, waste reuse also leads to cost savings and improves sustainability. Therefore, this short review aims to present and discuss the recently used methods of utilizing feather waste as sustainable and renewable insulation instead of traditional petroleum-derived materials. The father's low thermal conductivity ranges from 0.024 W/(m. K) to 0.034 W/(m. K), and it's chemical composition and microstructure effectively trap air and produce a good barrier. So, feather waste fibers can be used as an effective thermal and acoustic insulation material with the same or better performance than commercially available products. However, several significant barriers and limitations associated with the manufacturing process of feathers insulations were identified in this review. These limitations make the commercial development of insulation materials based on feather waste a challenge. They need to be appropriately addressed to realize the potential of feather waste as a reliable insulation material.

مواد العزل القائمة على نفايات الريش المعاد تدويرها: مراجعة

عبدالمنعم رعد عبدالمنعم[1]، بكرالدين محمد سامين[2]، ازهري عزمي مازالي[2]، عبداللطيف احمد جاد الله[3]، خالد فيصل سلطان[1]
[1] قسم الهندسة الكهروميكانيكية / كلية الهندسة/ الجامعة التكنولوجية / العراق.
[2] كلية الهندسة الميكانيكية، كلية الهندسة، الجامعة التكنولوجية الماليزية، جوهور، ماليزيا.
[3] كلية الهندسة/الشرقاط – جامعة تكريت/ تكريت - العراق.

الخلاصة

يتجه العالم حاليًا نحو إعادة استخدام النفايات في العديد من التطبيقات الصناعية مثل المباني والسيارات وغيرها، للقضاء على تأثير التلوث البيئي الناتج عن زيادة النفايات حول العالم. إلى جانب ذلك، يمكن أن تؤدي إعادة استخدام النفايات أيضًا إلى توفير التكاليف وتحسين الاستدامة. لذلك، تهدف هذه المراجعة القصيرة إلى تقديم ومناقشة الأساليب الحالية المستخدمة لاستخدام نفايات الريش كمادة عزل مستدامة ومتجددة بدلاً من المواد التقليدية المشتقة من البترول. إلى جانب الموصلية الحرارية المنخفضة التي تتراوح من 0.024 واط / (م · ك) إلى 0.034 وات / (م · ك) اعتمادًا على نوع الريش، يمكن استخدام ألياف نفايات الريش كمواد عزل حراري وصوتي فعالة بنفس الأداء أو أفضل من المنتجات المتاحة تجاريًا، نظرًا لتركيبها الكيميائي والبنية الدقيقة للريش، والتي تحبس الهواء بشكل فعال وتنتج حاجزًا جيدًا. ومع ذلك، هناك العديد من العوائق والقيود الهامة المرتبطة بعملية تصنيع عوازل الريش التي تم تحديدها في هذه المراجعة. تجعل هذه القيود التطوير التجاري لمواد العزل القائمة على نفايات الريش تحديًا ويجب معالجتها بشكل صحيح حتى يمكن تحقيق إمكانات نفايات الريش كمادة عزل موثوقة.

الكلمات الدالة: نفايات الريش، نفايات معاد تدويرها، مواد مستدامة، العزل الحراري، العزل الصوتي.

1.INTRODUCTION

A material's thermal insulation capability depends on its thermal conductivity value, where low thermal conductivity presents the best thermal insulation. Such capability is crucial for various industrial applications, especially for building insulation, where the global market estimated the use of thermal insulation materials in buildings was at almost 30 billion USD in 2021 [1, 2]. However, most insulation materials are synthetic plastic-based or mineral/glass wool, which correlates with various harmful environmental impacts, especially at the end of their life cycle [3]. Therefore, the need for more sustainable thermal insulation materials derived from either recycled or natural materials has arisen. In this context, feather waste from poultry farming presents a unique potential to be used as a sustainable thermal insulation material. Poultry consumption, in general, is growing globally, thanks to its low operating cost and the chickens' rapid growth. In Europe alone, people consume about 14,013,000 tons of poultry annually [4]. In other words, poultry is the primary source of animal protein. Global poultry consumption is expected to increase to about 14.9 kg/person/year by 2023 [5]. The high consumption of poultry leads to high production of feather waste, reaching 3.1 million tons of waste per year in the EU. The traditional methods of feather waste destruction are burial in landfills and incineration, which unfortunately contribute to air, soil, groundwater, and surface water pollution due to its highly toxic degradation process. As a result, the number of research works that have studied the novel applications of feather waste in various areas has recently increased [6–15]. In terms of the thermal insulation capability, feathers are considered a sustainable thermal insulation material that can be used in many thermal insulation applications due to its low thermal conductivity, ranging from 0.024 W/(m. K) to 0.034 W/(m. K), depending on the feather's types [16]. This low thermal conductivity range is due to the feather's chemical composition and microstructure, which effectively traps air and produces a good thermal barrier. A feather's microstructure example is shown in Fig.1. which depicts the hollow honeycomb structure that contributes to the low thermal conductivity of the feather [17]. Nevertheless, feathers' thermal degradation occurs at about 180 °C, which limits their potential to be used in applications involving high-temperature processes [18].

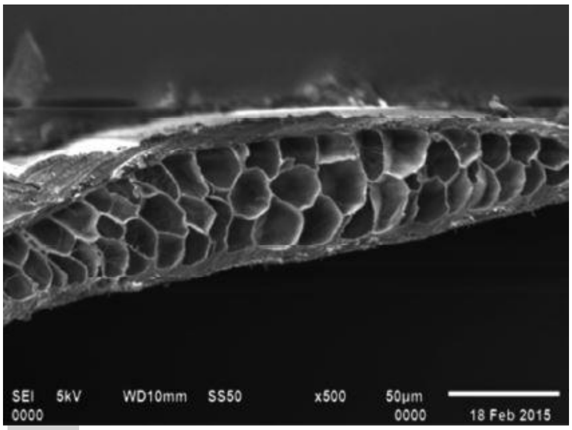

Fig. 1 SEM Image of the Cross-Section of a Barb Showing a Hollow Honeycomb Structure [17].

Feather waste is also considered one of the lightest natural waste materials with a density of 0.68 g/cm3 [19], where it has a skeletal density of about 1.01 g/cm3, compared with cellulose, wool and hemp fibers at about 1.50 g/cm3, 1.30 g/cm3, and 1.39 g/cm3, respectively [19, 20]. The low density and thermal conductivity values make feather waste ideal for thermal insulation in many industrial applications. Furthermore, the thermal conductivity of sustainable building insulation products has been reviewed, and these are being used in a range of applications to achieve energy efficiency targets [21]. The sensitivity to humidity leads to a reduction in the thermal performance (thermal conductivity and thermal diffusivity) of natural insulation materials [22, 23]. Using fibers such as recycled paper mill waste in cement improves the mechanical properties and reduces the thermal conductivity of the lightweight cementations materials [24]. Based on the determined physical and thermal characteristics of the insulation materials made from textile wastes using needle punching technology, it is considered applicable as thermal insulation material in buildings [25]. Also, nonwoven thermal insulation materials have been prepared from recycled polyester fibers and wool, which are considered appropriate for green building insulation [26]. Recently, using feather waste as an insulation material thermally or acoustically in different applications is limited. This paper aims to review the latest works that contributed to utilizing and developing feather waste as an insulation material in many applications. Furthermore, this paper also highlights and discusses the significant barriers that hinder the application of feathers as insulation materials. These highlights and discussions motivate researchers to explore new research frontiers that use the feather's properties as a sustainable material in many insulation applications.

2.FEATHER WASTE AS INSULATION MATERIALS.

Plastic envelopes are considered one of the main materials used as artificial insulations [3, 27]. In 2005, the United States consumed about 28.9 million tons of plastics in the packaging industry, and only about 5.7% of them were recycled, while most were disposed of in landfills [28]. Most currently available plastics in the market are derived from petroleum-based resources, and these materials are non-biodegradable. On the other hand, feather waste is considered a new sustainable solution that, unlike these plastics, will reduce pollution due to its biodegradability.

2.1. Thermal Insulation

Reddy N. et al. [29] developed biodegradable and inexpensive thermoplastics based on inexpensive poultry feathers as a renewable and sustainable resource in the industry by alkaline hydrolysis and crosslinking with citric acid. In their work, various alkali concentrations were used for hydrolyzing feathers, and the glycerol used as a plasticizer was crosslinked with citric acid to improve water stability. Alkali hydrolyzed feathers were compression molded into films, as shown in Fig. 2 (a), with 5.9 MPa tensile strength and 31.7% elongation; however, the wet strength was poor. Meanwhile, for the feather films crosslinked with citric acid, the tensile strength was 1.9 MPa, and the elongation was 24.6% after being in 90% humidity at 21 °C. These findings mean that the alkaline hydrolysis and citric acid crosslinking provide a chance to develop cheap and biodegradable thermoplastics from sustainable and renewable poultry feathers. A new biodegradable polymeric material based on chicken feathers (CFs) with selected biopolymers (polybutyrate adipate terephthalate, polylactic acid, and a polylactic acid/thermoplastic copolyester blend) was developed by Aranberri et al. [30], as shown in Fig. 2 (b), in applications such as panel components for flooring or building materials. This CF-based material can be a biodegradable alternative to wood-plastic composites in the building industry. The biocomposites' mechanical, thermal, and physical properties were investigated based on the effect of the CFs concentration ratio and the type of biodegradable matrix. The results indicated that the high concentration ratio of CFs bio-composites improved the thermal-insulating of the materials by 18.9% and increased the tensile strength from 13.7 to 24 MPa with lightweights by 20.31% compared to the neat bio-plastics. Also, the adhesion between the polylactic acid matrix and the CFs has been investigated. An improvement in the wettability of the CFs by 17% was obtained with the alkali treatment and a plasticizer additive like polyethylene glycol. In another work, Aranberri et al. [31] replaced fully petroleum-based foams with bio-foams containing up to 45% of bio-based materials in thermal insulation applications. In their work, sustainable rigid polyurethane foam reinforced with CFs was prepared by using castor oil as a bio-based polyol to formulate the foams, as shown in Fig. 3. It was found that adding CFs to a bio-foam improved the thermal insulating properties by reducing the heat flux density within the bio-foam. The results obtained in their work proved that incorporating CFs into a rigid polyurethane foam modified the cell structure of the foams, affecting their physical and mechanical properties by decreasing the compressive strength by 25% and improving the thermal insulation properties by 20%.

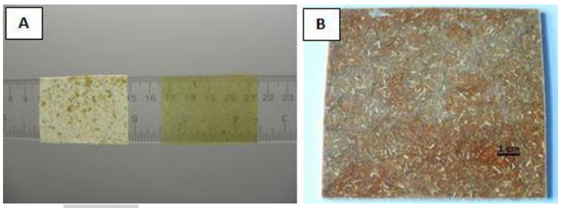

Fig. 2 (A) Thermoplastic film (right) compression molded from the hydrolyzed feather compared to the untreated feather (left), which stayed unmelt under similar compression conditions [29], (B) Chicken feathers bio-composites panel [30].

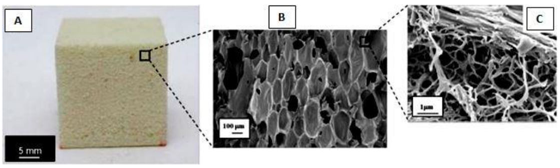

Fig. 3. A) Cubic specimen of RPU15 bio-foam, B) and C) FESEM images of the RPUF15 with different magnifications [31].

Dieckmann et al. [32] reported that the air-laid nonwoven (Fig. 4) feather fiber liners could displace expanded polystyrene for delivering chilled and frozen foods and others susceptible to degradation by high temperatures during delivery. The authors conducted experiments involving monitoring the time-temperature profile of meat substitute materials and coolants stored inside cardboard boxes lined with thermal insulation. The results showed that the feather fiber composite insulation had comparable thermal performance to expanded polystyrene and may even outperform expanded polystyrene under some conditions by a factor of 3 or more. In another work, Dieckmann et al. [33] compared the air-laid nonwoven materials that had a high fiber content of CFs with a range of commercially available thermal insulation materials for buildings manufactured from hemp, denim, sheep wool, and mineral wool. They found that air-laid feather-fiber fabrics had comparable performance to other fibrous materials. Their thermal conductivity reached 0.033 W/(m K) with a low density of 59 kg/m^3 due to the void structure that effectively traps air.

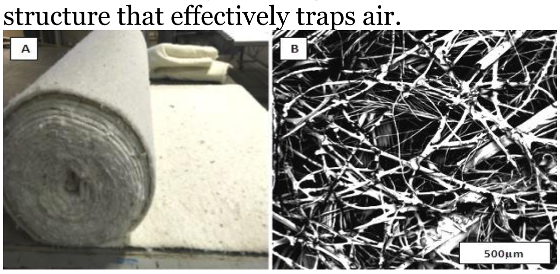

Fig. 4. A) Typical air-laid nonwoven feather fiber composite material, B) SEM image of the microstructure of air-laid nonwoven feather fiber composites [32].

Next, Mrajji et al. [34] developed nonwoven insulation material based on CFs waste as a new insulation material in the construction and automobile sectors. The developed materials were treated with ethanol, acetone, sodium dodecyl sulfate, hydrogen peroxide, and conventional detergents. The new nonwovens exhibited excellent insulation performance, where the thermal conductivity ranged from 0.0313 to 0.04465 W/(m. K). The treatments' results showed efficacy at concentrations between 1 and 2%. However, the best results were attributed to the treatment with detergent imopon DPL-V and sodium dodecyl sulfate with no significant differences in structure and chemical composition. This finding was also confirmed by energy-dispersive. Subsequently, Zhao et al. [35] mixed the feather fibers with 25 wt% of short (6 mm) bi-component fibers and 12.5 wt% of 32 mm long cotton fibers to develop a new thermal insulation material. This material was used to insulate pipelines transporting liquid natural gas as a low-temperature application. These newly developed biomaterials had extremely low thermal conductivity, ranging between 0.020 and 0.036 W/(m. K). Also, they retained high impact resistance at low temperatures compared to the commonly used foamed nitrile rubber. Soekoco et al. [36] studied the effects of varying the CFs orientation on the thermal insulation properties of the CFs to produce an optimal nonwoven insulation material. The results indicated that nonwoven fabric made from CFs waste with unidirectional orientation had six times tensile strength higher than random orientation. It provided the best hot air insulation by about 4 °C, while the random orientation of CFs showed the best insulation performance for the cold air by about 3 °C. Choudary et al. [37] made a series of nonwoven mats by adding several levels of CFs fiber at the range between 10 and 60% using pre-vulcanized latex as a binder. The results indicated that the tensile and tear strengths were similar to the latex adhesive strength, while the thermal conductivity was better than the latex adhesive by 15%. The ceiling board from the waste carton and portland cement reinforced by 10% of CFs was prepared by Odusote et al. [38], where the findings showed that the developed ceiling boards of 80% cement, 10% carton, and 10% CFs could compete favorably with most available ceiling boards in the market in terms of good density of 700.7 kg/m^2, compressive strength of 10.3 N/mm^2, modulus of elasticity of 1.60 GPa, modulus of rupture of 2.2 MPa, and thermal conductivity of 1.077 W/m. K. Meanwhile, Kolajo et al. [39] studied the combination of waste paper and CFs in several ratios (0%, 5%, 10%, 15%, and 20%) to produce decorative wall panels. The results showed that the increase in the CFs ratios gradually decreased the thermal conductivity, reaching 0.154W/m. K at 20% of CFs. Also, 5% CFs had the highest impact strength of 3193.84 J/m, while optimum water absorption and thickness swelling were achieved at 15% of CFs.

2.2. Acoustic Insulation

Few studies have reported the uses of CFs and their effect on acoustic insulation performance. Marta et al. [40] fabricated sound-absorbing nonwoven materials using CFs wastes to evaluate the acoustic insulation performance and their fabrication processes' environmental impacts using the life cycle assessment methodology and then compared the results with stone wool as a conventional insulating material. The study showed that it was possible to fabricate CFs-wool nonwovens incorporating up to 50 % of CFs. The new material showed similar acoustic properties to stone wool, even behaving better for frequencies below 2200 Hz. The sound absorption coefficient reached more than 0.95 at 2000 Hz, which was considered a proper performance of the nonwoven materials using CFs wastes compared to commercial acoustic insulators. Increasing the CFs amount decreased the environmental impacts of nonwoven materials containing CFs-wool, as the study results of the life cycle assessment showed. In another study conducted by Ansarullah et al. [41], an acoustic insulation panel was created by combining two materials of CFs and PVAC material. The results indicated that using CFs with PVAC material improved the acoustic insulation of the used panel, i.e., the sound absorption coefficient reached 0.59. Dieckmann et al. [42] investigated using feather fibers to produce nonwoven feather fiber composite mats as an alternative to oil-derived synthetic plastics sound absorption materials. The authors found that the air-laid nonwoven feather fiber mats improved the sound absorption coefficients, particularly in the low-frequency ranged between 250 to 800 Hz from 0.4 to 0.88, compared to cellulose fiber mats and mineral wool mats with the same thickness, i.e., 50 mm. Further, Kusno et al. [43] compared the sound absorption coefficients of the prepared CF absorbers samples of various densities and thicknesses (25mm, 50, and 75mm) with conventional glass wools made for the same densities and thicknesses. The results showed that CFs had a potentially good sound-absorption performance. For some frequencies, more than 800 Hz, it had a sound-absorption coefficient higher than the conventional glass wools, in some cases fluctuating between 0.7 and 1. Nazim et al. [44] investigated the sound-absorbing properties of a nonwoven web made of CFs using different binding materials using the thermal bonding method. The results showed that the CFs' nonwoven web could be used as sound insulation because of their good sound-absorbing properties. Moreover, the sound absorption coefficient improved as the material's thickness increased. Also, the CFs' nonwoven web was a bad sound isolator at low frequencies. It was possible to obtain a material with an approximate thickness of 37 mm with a 0.7 sound absorption coefficient at a frequency of 200 Hz. Next, Dance et al. [45] determined the nonwoven CFs' sound absorption coefficients over a range of frequencies from 80 and 1,600 Hz. The results indicated that the sound-absorption properties of the tested samples were high, exceeded 0.70 for frequencies above 800 Hz, and were low for frequencies below 200 Hz. On the other hand, Abdulmunem et al. [46] developed a new bio-composite material based on CFs for different mass fractions (25 %, 50 %, and 75 %) integrated with phase change materials within polyvinyl chloride (PVC) panels as building inner envelopes. The results indicated that the integration of WCF at a ratio of 75 % with a PCM within PVC panels improved the sound absorption coefficient by 9 %.

3. BARRIERS AND LIMITATIONS

Based on all the reviewed works, it can be summarized that producing thermal and acoustic insulation materials from feather waste involved many processes, such as disinfection and washing, treatment of the clean and dry feathers into fibers, and producing air-laid nonwoven feather-fiber materials. Furthermore, it is also vital to select the best binder materials, feather waste mixing ratios, thicknesses of the mat, and others based on the targeted applications, to achieve a low thermal conductivity. As a key conclusion, it is possible to manufacture high-performance thermal and acoustic insulation materials from feather waste with the same or better properties than those manufactured from wool, hemp, and denim. Also, it can be summarized the main critical barriers that prevent utilizing feather waste in the manufacturing of thermal and acoustic insulation materials as follows: -

1. Restrictions on using CFs; one of the crucial problems in many countries like the UK is the restriction on using feather waste, which is exported as a low-grade animal feed [47]. This restriction provides little incentive in the feather waste industry, such as disinfection and washing processing lines necessary to produce clean feathers. Therefore, feather waste is expensive, and it is difficult to source suitable raw materials.
2. Biodegradation decomposes; the processing time between the collection and the washing/disinfection must be reasonably short to avoid the biodegradation of feather waste.
3. Although viable fire-resistant treatments exist, the fire resistance of the thermal insulation materials is clearly a crucial concern [48]. Implementing fire-resistant treatments increases the cost and saps the

feather waste product's commercial viability.

4. In confined spaces, there is a significant barrier to using feather waste products for thermal and acoustic insulation, as in the automotive industry, due to the odor and production of volatile organic compounds (VOCs) [1].

4. CONCLUSIONS

Based on the results of the reviewed studies in the present work, it can be concluded that the feather waste fibers can be used as an effective thermal and acoustic insulation material in many applications after being disinfected and cleaned due to their low thermal conductivity. This low thermal conductivity is due to its chemical composition and microstructure, which effectively traps air and produces a good thermal barrier. The thermal conductivity can be further reduced by increasing the feather waste's density. Therefore, it is possible to manufacture sustainable high-performance thermal insulation products from feather waste with the same or better performance than commercially available products. However, this review also highlights several significant barriers and limitations associated with the manufacturing process of feathers insulations. These limitations make the commercial development of insulation materials based on feather waste a challenge. These limitations should be adequately addressed so that the potential of feather waste as a reliable insulation material can be realized.

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