The Social Construction of Biobased Materials and Aviation

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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In 2018 and 2020, heatwaves struck Japan, reaching record temperatures of 106 degrees Fahrenheit and 104 degrees Fahrenheit for a month, respectively. In the 2018 heatwave, it was estimated that 1,000 people died (Merino, 2020). Indirectly, the heatwave also caused power outages throughout the nation. This event was the first of its kind to be proven by attribution science, a developing field associating specific events with climate change, to be definitively caused by anthropogenic climate change (Imada et al., 2019). These record temperatures were recorded at a global increase of average temperature by around 1.25 degrees Celsius. After the Japanese heat waves was the 2022 European heatwave, which saw up to 60,000 excess deaths across the EU (Ballester et al., 2023). With each passing year, climate change worsens; its effects on both people and the planet increase in proportion. Natural disasters, disease, habitat loss, and other consequences combine to make the planet a more dangerous place to live, but there are ways that humanity can reduce or even reverse climate change. To combat climate change's effects, measures must be taken wherever possible to reduce the anthropogenic emissions that contribute towards the greenhouse effect. There is one area that disproportionately contributes towards these emissions while also having relatively simple solutions.

Aviation makes up 5% of all anthropogenic climate change (Lee et al., 2020, p.2). A simplified graphic produced by the BBC shows that combined, domestic and long-haul flights have higher emissions per passenger per km travelled than all other forms of transportation combined (Timperley, 2020). Advances in fuel efficiency, structural design, and engine efficiency have all helped to lower aviation emissions, but the fact remains that per passenger per km, aviation is still the highest emission-producing mode of transport. One way to solve this problem would be to use biobased materials, which can be grown sustainably and can improve the strength-to-weight ratio of the aircraft. Combining active carbon sequestration through photosynthesis and decreased emissions from increased efficiency can lower aviation's net emissions. Through the Social Construction of Technology (SCOT), a theory positing that technologies are subject to influence from social groups as the tech develops, various stakeholders and their concerns will be examined. First, a brief overview of biobased materials is provided (Bijker, Hughes, and Pinch, 1987).

Biobased materials are any material derived from biological matter. They have many use cases as foams, epoxies, rubbers, or as fibers. Fibrous biobased materials can be used as composite materials in the same way that carbon fiber is. While not necessarily supplanting carbon fiber, the usage of biobased materials as a composite allows for further increases to the strength-to-weight ratio. By reducing the overall weight of the aircraft, the aircraft's efficiency is increased; less fuel would need to be burned for an equivalent flight. Lowered fuel expenditure of course means lowered carbon emissions. Biobased materials also have a more active effect on carbon emissions; specifically, biobased materials can facilitate carbon sequestration – drawing carbon dioxide directly from the air (Arehart et al., 2020). This happens primarily during the preproduction phase as the plants photosynthesize before being used to manufacture biobased materials. Arehart and colleagues also show how other materials, namely cementitious materials, also aid in carbon sequestration via carbonation. Although the amount of carbon sequestered by cementitious materials is "non-negligible," the lifetime carbon emissions of cementitious materials still far outweigh that of biobased materials (Arehart et al., 2021, p. 18). While the scope of this paper is limited to aviation because of the specialized parts and design planes require, biobased material composites can and should be applied to other goods such as vehicles, buildings, and houses. Arehart et al. conclude that buildings are the best containers of both biobased materials and sequestered carbon; this begs a question about aviation's relevance to biobased materials and reducing emissions. These materials are still relevant to aviation because of their other properties, namely their increased strength-to-weight ratio. Lighter planes are more efficient and produce less emissions. Sequestration is a helpful property, but the nexus between aviation and biobased composite materials is still the weight factor. Still, the production of biobased materials actively reduces free carbon present in the atmosphere, regardless of what the material is eventually used for. If the lifetime carbon emissions of biobased materials outweigh the lifetime carbon emissions of traditional aerospace materials (TAM), the usage of biobased materials is considered valuable.

Using SCOT, several stakeholders become clear. These stakeholders are engineers, government, industry, and the public. Each stakeholder has overlapping concerns that can be categorized as either performance, sustainability, or cost concerns. These concerns must be addressed for the smooth implementation of biobased materials and biobased material composites (BMC) to occur. Engineers have primarily performance concerns, while sustainability is shared between the public and the government. Cost is shared between industry and the government. These concerns will be examined in sequence below.

As relevant stakeholders are examined, stakeholder concerns can be largely traced back to the properties of the BMCs themselves as materials. The financial value, public and political trust, and industry risk assessment all rely on the material properties of the BMC. It is assumed that even the increases in sustainability and reductions in embodied carbon emissions come second to the safety and engineering concerns. The Federal Aviation Administration (FAA) boasts, “during the past 20 years, commercial aviation fatalities in the U.S. have decreased by 95 percent,” attributing the agency’s success to “a longstanding commitment to… an open and collaborative safety culture” (2018). Thus, it becomes paramount to prove to the engineers who will be working with BMCs that BMCs are a practical alternative to traditional aerospace materials.

From an engineer's perspective, the material performance is the most important aspect, as biobased materials must be shown to fit aerospace clients' requests. Using biobased composites results in tradeoffs of material performance when compared to the standard bulk material. It was found that adding date palm fibers (DPF) to a nitrile rubber matrix resulted in increased stiffness, compression resistance, and tear strength, all scaling directly with the fiber weight percentage (El-Shekeil, 2024). The study also showed that adding DPF reduced the tensile strength significantly, but the authors propose that this could be due to fiber agglomeration during composite production, and further studies should be conducted to fully explore the limits of this particular material. The tensile strength did not decrease with increasing fiber weight percentage, further pointing towards the explanation of fiber agglomeration rather than the fiber itself being weak. Although this composite might not be able to fulfill the same role as nitrile rubber in tensile applications, it now has other uses in industry. This comparison also ignores the lifetime carbon emissions of both materials. The study does not elaborate on the sustainability aspect of the composite, but given the composite's biobased status, the lifetime carbon emissions of the composite must be lower than that of the pure nitrile rubber. These decreases in lifetime carbon emissions would scale further with increases in fiber weight percentage.

Applying biobased material composites to purely aerospace structures is not as promising. A conference presentation from 2014 showed that of three tested BMCs, only one was truly practical to replace TAMs as a potential wing material (Boegler et al.). Still, this viability was conditional; the ramie fiber case had less ideal mechanical properties than aluminum, but it also had lower structural weight. Technically, this ramie fiber composite could be used as a substitute for aluminum in an airplane's wings, but these lowered mechanical properties may mean that more of the material would need to be used, thus making the lowered structural weight advantage moot. The study used an Airbus A320-200 as its test model, so although the BMCs showed lower mechanical performance, perhaps there is a usage for them in small craft or smaller commercial aircraft. Furthermore, the study examined the possibility of using BMCs to replace a wing; replacing parts of the fuselage, control surfaces, or even simple struts was not considered in the simulation. More research and simulations must be done to find, if any, possible use cases for biobased materials as aircraft parts. The importance of the structural use case cannot be overstated; if BMCs are found unable to replace TAMs as structural parts, safety considerations take precedence and BMCs in aerospace will never be a possibility.

Outside of structural concerns, aerospace materials must be able to operate in a broad range of thermal conditions. Stratospheric temperatures are low, but specific parts of the plane are hot, like the engines or points with high friction. There are reasonable concerns about the flammability of materials based on plant fibers, but a review of various flame-retardant biobased films showed that biobased films had the potential to match the viability of standard synthetic polymers. For example, mycelium was found to have potential as "an affordable, environmentally friendly, and fire-safe substitute for synthetic polymers in binding matrices" both standalone and in wheat-grain composites (Zhang, 2023). The same study found that coating bagasse paper in cellulose nanocrystals (CNC) increased fire resistance by up to 27.5%, and a thermoplastic polymer composite made of arrowroot starch and fibers had a significant increase in thermal stability. Clearing thermal conditions is another hurdle BMCs must overcome to be accepted by engineers, and future studies will have to observe BMCs in real-world aerospace conditions.

Given these considerations, BMCs have not been definitively shown to be practical in all aspects that traditional aerospace materials are. More research must be done to bring BMCs to the same mechanical standards as TAMs. This assumes that BMCs have the capability to match TAMs, but the important criterion is the BMCs strength to weight ratio; if the rate at which the BMC's weight decreases outpaces the rate at which its mechanical properties fall, if at all, then the material deserves serious consideration for research and development. Outside of mechanical performance, BMCs function as well as traditional materials, at least as far as rubbers and flame-resistant coatings are concerned.

Engineers are not the only stakeholders concerned about materials suitability. The government, acting through the FAA, has its own process for approval. While the FAA does not clear materials themselves for use, it does mandate an airworthiness certification process for all registered aircraft. The certification process is split into either a standard certification or a special certification. This special certification is what BMC-based aircraft will likely have to apply for, as this categorization encompasses experimental research and development aircraft among other types. This certification process is thorough and outside the scope of the paper, but it does beg certain questions about BMCs. Currently, BMCs do not have the same mechanical and structural properties as TAMs; this can be compensated for by altering designs. However, when these designs are altered, they are subject to approval from the FAA, and it will not always be the case that these modifications will be accepted as airworthy. This design consideration further limits the potential usage of BMCs.

The public and government have their own concerns, namely worry over biobased materials' suitability to replace traditional aerospace materials and whether they are truly sustainable or not. The material suitability has already been addressed in the previous section, where concerns over material performance have been raised and hopefully improved. The growing climate awareness in the public sphere gives climate-conscious citizens a heightened sense about company greenwashing, a way a company can appeal to climate-conscious citizens by superficially supporting environmental causes without addressing the company's true effects on climate change. In the following section, the sustainability of biobased materials and the biorefinery will be reviewed.

Sustainable effects conferred by the usage of biobased materials should not be offset by the carbon emissions of their production. If the embodied carbon emissions of biobased material composites were greater than the ECEs of traditional aerospace materials, there would be little point in adopting BMCs from a sustainable viewpoint. Thus, the production of BMCs must be done through a biorefinery. The idea behind the biorefinery is that each step of the agricultural process would be harnessed in a sustainable way to ensure that the production of biobased materials would at least cause less emissions than aerospace materials. In ideal circumstances, this process would be carbon-neutral, if not even carbon-negative (Meer, 2017, pp. 3-4). Proving that these biorefineries truly are carbon-neutral or carbon-negative is a crucial step to gaining public trust. Otherwise, biobased material companies would be seen as greenwashing, and public support for even changing from traditional aerospace materials would be dampened.

The biorefinery creates sustainable biomaterials with the following steps. The principal idea behind a biorefinery is that industrially farmed amounts of plant matter are then turned into a processed item, like grain, which can then be split up to produce food items, biofuels, biomaterials, and then biochemicals. A pyramid contrasting price versus volume shows how these four products are categorized (Langeveld et al., 2010, p. S-148). Each step in the biorefinery can be sold as is or used to produce the next highest step; feed is processed in biofuels, which are used in tandem with excess fibers to create biomaterials, which can be processed into biochemicals. These products are structured in a pyramid, with low-cost high-supply items such as feedstock being at the bottom of the process pyramid and high-cost low-supply items such as biochemicals being at the top of the process pyramid. Because of the nature of being biobased, the idea is that the carbon sequestration occurring during the preproduction phase is enough to offset any carbon emissions that occur during the entire refinement process. For this paper's purpose, only the steps until refinement into biomaterials are considered. Langeveld and colleagues mention a key concern being that this bio-refinement process takes away from available food stock, making local populations vulnerable to famine. However, they argue that these people are likely net food consumers already, so the added value of completing the bio-refinement process would allow for more available food than simply growing the crops for food (p. S-150). While counter-intuitive at first glance, the added value of completing the process comes from stripping as much value from the crop as possible, thus reaching the low-supply but high-price products. These products can then be sold, and more food can be bought than if the initial supply of food was left unprocessed. With this implementation, biorefineries become sustainable engines of production and can enrich the local communities they are built in. Langeveld et al. have created a theoretical framework for how a large-scale biorefinery might be executed, but they do not have a working model, limiting any potential policy governments or industry might enact to implement this model.

Industry concern holds another factor equal to sheer performance: the cost to implement. This implementation costs more than just the raw materials to produce biobased materials; this includes retooling and overhead costs. This examination must also consider the turnaround time of changing from production of synthetic materials to biobased materials. Time lost is money lost, so the long-term cost savings of using biobased materials must outweigh the raw material cost along with these other expenses. Thus, we must examine the initial raw cost of production first. The complicated time-dependent costs will not matter if the raw material cost is too high.

Biobased materials have unclear costs associated with their usage. In the Airbus A320 study, it was found that the cost of the ramie fiber composite wing would be anywhere between $14400-31100 (Boegler, 2014, p. 4). In comparison to the $21200 cost of an aluminum wing, it cannot be conclusively argued that the use of biobased materials would reduce the cost of the wing. However, it is still possible that the lifetime profitability of the composite wing is still higher from reduced operating costs. Ramie composite wings were between 12 and 14 percent lighter than standard aluminum wings. In an airplane, where saved mass is critical to improving performance, having 12 to 14 percent lighter wings creates an incentive to further study of biobased materials. While the Airbus study focused on the wings, a different aspect of cost-reduction could be achieved through the usage of biobased materials. Biobased materials may have considerable energy saving potential; according to an anonymous interviewee, “a social housing construction built with a bio-based insulation solution used 70% less energy than conventional synthetic material” (Dams et al., 2023, p. 769). Anonymizing these interviewees helps to prevent any issues about conflict of interest, but it does mean that the interviewee might not be particularly informed about the subject they are talking about. However, the aggregate opinion of interviewees in this study was that using biobased materials helped to reduce energy costs, so some level of credence is given to the interviewees’ conclusion. Biobased materials might have an initially higher cost due to the material itself and design considerations to accommodate them, but their long-term energy and cost-saving effects are significant. This example referenced building insulation, but substituting insulation materials found in aircraft now with biobased materials would have similar effects.

The more complicated time, retooling, and overhead costs do not have much information or study in academic fields. Widescale adoption of biobased materials has not occurred anywhere, and models of doing so are usually theoretical, such as Langeveld's model. Estimations for time and cost can still be made based off the model by combining time and cost models for a farm and an oil refinery. By modeling each step of the biorefinery in isolation rather than holistically, general estimates can be made to compare to standard industrial manufacturing. This analysis should be reserved for authors more familiar with the systems involved in industrial agriculture, refinement, and fuel, but even the possibility of conducting such an analysis will influence industry professionals. Having the biorefinery be a concrete implementation strategy rather than a topic of academic research provides a more grounded and practical aspect.

Using the Social Construction of Technology, the concerns of engineers, governments, the public, and industry have been sorted into categories of material suitability, sustainability, and cost. Biobased material composites have not reached the same level of mechanical performance as traditional aerospace materials, but in other areas such as thermal suitability, BMCs have met the same or similar levels as TAMs. BMCs can be sustainable through the biorefinery, which primarily absorbs carbon during the preproduction phase. BMCs are also much lighter than TAMs, making aircraft more efficient and reducing emissions there. Despite the promising results, it is inconclusive whether BMCs are cost-effective. BMCs can reduce energy consumption and thus cost, but the initial cost of not just using BMCs, but retooling and the turnaround time of implementing biorefineries will dissuade industry leaders from adopting the technology. Thorough time and cost analyses of biorefineries using analogous structures such as industrial farms and oil refineries will be needed to have industry leaders conclude that biobased materials are a technology worth pursuing. Overall, biobased materials are just one of many solutions to the various areas surrounding the complex issue of anthropogenic climate change. Even if biobased materials are not the best way to reduce aviation's impact on emissions, any potential for reduction should be seriously considered.

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